بسم الله الرحمن الرحيم

Sudan University of Science & Technology

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Design and Simulation of CubeSat Transceiver

تصميم ومحاكاة جهاز إرسال وإستقبال لقمر صناعي مكعب

A thesis Submitted in Partial Fulfillment of the Requirement for the Degree of M.Sc. in Electronics Engineering (Communications Engineering)

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الآيــة

بسم الله الرحمن الرحيم

قال تعالى: {يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَات}

[سورة المجادلة: 11]

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Abstract

This thesis conducting to have a discussion about communication subsystem of Cube Satellites, considering ISRASAT1 prototype as a focal of point with detailed description of CubeSat subsystems, transceiver components and design procedures to reach final shape of the project. the output of this research is a consistent design of CubeSat transceiver based on ISRASAT1 specifications by using some software tools such as Advanced Design System **ADS** for Ultra Hight Frequency mixer and High Frequency Structural Simulator **HFSS** for antenna design. Hardware implementation has been done for **TNC** and **AFSK** modulator based on (Arduino Uno kit) with two Walkie -Talkies to verify data transmission between Tx and Rx.

This study realized the main mission of ISRASAT1 prototype as transfer data between CubeSat and ground stations over wireless link using UHF band 433MHz for telemetry as well as all of design procedures achieved after calculate the link budget for 450 km distance between CubeSat and ground station with considered losses and gains. Also, UHF Mixer has been designed and obtained RF signal 433 MHz with -14.9 dBm after adding matching networks at the input and output of mixer and applying BPF with 8 dB gain at the output of mixer. Dipole antenna has been designed to meet ISRASAT1 specification with good results about 3dB gain, 2.9 VSWR and -5.9 dB as insertion loss.

المستخلص

إهتمت هذه الرسالة بإجراء مناقشة حول النظام الفرعي للاتصالات في الأقمار الصناعية الصغيرة مع الأخذ في الإعتبار النموذج الأولي لإسراء سات واحد كمركز محوري للبحث مع وصف تفصيلي لنظم الكيوبسات الفرعية الأخرى ومكونات جهاز الإرسال و الإستقبال بالإضافة إلى إجراءات التصميم للوصول إلى الشكل النهائي للمشروع.

الناتج من هذا البحث هو تصميم متناسق لجهاز الإرسال والإستقبال لقمر صناعي مكعب إستنادًا إلى مواصفات إسراء سات واحد باستخدام بعض برامج المحاكاة الحاسوبية مثل برنامج (آى دي إس) لتصميم مازج فائق التردد و برنامج (اتش اف اس اس) لتصميم الهوائي. وقد تم تنفيذ كل من دائرتي الـ (تي ان سي) ومعدل إزاحة التردد الصوتي بإستخدام لوحة (أردويينو أونو) مع جهازين لاسلكي للتحقق من نقل البيانات بين المرسل والمستقبل. حققت هذه الدراسة الغرض الرئيسي لنموذج إسراء سات واحد الأولي الذي يتضمن نقل البيانات بين القمر الصناعي والمحطة الأرضية عبر وصلة لاسلكية باستخدام النطاق فائق التردد 433 ميغا هيرتز للقياس عن بعد.

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List of Abbreviations

ADCS	Attitude determination and control system
ADS	Advanced design system (software program)
AFSK	Audio frequency shift keying
AM	Amplitude modulation
AX.25	Amateur data link layer protocol
BJT	Bipolar junction transistor
BPF	Band pass filter
CAD	Computer-aided design
COMM	Communication system
COST	Commercial on the shelf
CubeSat	Cube satellite
CW	Continues wave
DC	Direct current
EEPROM	Electrically erasable programmable Read-only memory
EPS	Electrical power system
FM	Frequency modulation
FSK	Frequency Shift keying
GPS	Global positioning system
HFSS	High-frequency structure simulator (software program)

IF	Intermediate frequency
IL	Insertion loss
ISRA	Institute of Space research and aerospace
I^2C	Serial communication protocol
LEO	Low earth orbit
MCU	Microcontroller unit
NCR	National council for research
OBC	On board computer
RF	Radio frequency
RF	Radio frequency
SPI	Serial peripheral interface
SSB	Single side band
TNC	Terminal node controller
TT&C	Telemetry, tracking and command
UART	Universal asynchronous receiver transmitter
UHF	Ultra-high frequency
VHF	Very high frequency
VSWR	Voltage stand wave ratio
WPM	Word per minute

List of Symbols

bps	Bit per second
C	speed of light in vacuum (Constant)
D	Distance
F	Operating frequency
Gt	Transmitter gain
Gr	Receiver gain
Lfs	Free space loss
Lr	Receiver losses
Lt	Transmitter losses
Γ	Reflection coefficient
Pr	Received power
Pt	Transmitted power
1U	One unit
2U	Two unit
3U	Three unit
Z_0	Characteristic impedance
Z_l	Load impedance

Chapter One: Introduction

1.1 Preface

Cube satellites introduced 18 years ago by Stanford University and California Polytechnic State University (Cal Poly) in order to enable university students, emerge into space technology. Cube Sat standards define the satellite to be not greater than 10 cm cube of volume (i.e. one liter), and not greater than 1.33 kilograms of mass.

Despite the CubeSat standards constrains such as size, weight and power limitation due to the use of small batteries and solar cells, small satellites are considered as a good solution for research and development in the field of space technology.

ISRASAT1 (ISRA Sat One) is a research project aims to design and launch a cube satellite, which is approved by the Scientific Council of the National Center for Research (NCR) and funded by the Ministry of Finance. The project was launched in 2015 by the Institute of Space Research and Aerospace (ISRA), which is one of the research institutes of NCR. Project research team of ISRASAT1 is composed of researchers from ISRA, as well as other part time researchers.

ISRA holds all responsibilities of products (software and hardware), research published data and intellectual property of project. I have obtained permission to publish this data since I was part of research team.

The main mission of ISRASAT1 satellite is to send telemetry data, a beacon signal and image data to ISRA ground station. A digital camera carried by the satellite acquires the image. The satellite may design to receive command signals from the ground station to control some of its functions. Hence, in order to accomplish its mission, a beacon transmitter and a telemetry data transceiver designed separately.

The beacon transmitter has fully designed and implemented by ISRA research team for ISRASAT1 prototype. However, a ready-made telemetry data transceiver has selected and purchased to use in the first phase of the project. In phase two of ISRASAT1 project, a special onboard communication subsystem will develop, which requires design and simulation before implementation in order to assess its performance. The design includes performing a good survey for available components under a specific selection criterion to meet specifications of the project.

Small satellites divided into three categories based on satellite mass and size. Those categories are micro satellites, Nano satellites, Pico satellites and Fimto satellites. Nano satellites have a mass from 10 kg to 1 kg, which is the mass of one-unit (1U) CubeSat. According to CubeSat standard, satellite must have a size of 10 cm^3(10 x 10 x 10 cm) and one-kilogram 1U at most. In addition, there is ability to combine up to three units to produce 3U satellite has a mass of about 3 kg **[1].**

After launch of the satellite into space, there is no way to control it without communication system, i.e. "Without any way to communicate, the CubeSat would quickly become space junk". Hence, we won't be missing this important subsystem while designing the satellite.

In addition, there are three approaches when selecting communication subsystem for a CubeSat: buying COTS (Commercial on the shelf) transceiver, purchasing one designed for terrestrial use and modifying it, or building a transceiver from individual components **[2].**

1.2 Problem Statement

Ready to use transceivers for small satellite are very expensive and may not meet the exact specifications of communication link to execute mission properly. Also, there are some constrains face the designer throughout the designing process such as size, weight and power consumption of CubeSat transceiver electronics components, which restricts the options for compatible components to be selected.

1.3 Proposed Solution

In order to overcome the problems of high cost and unavailability of ready-made transceivers, design of CubeSat transceiver has been proposed.

1.4 Objectives

The main objective of this study is to develop a special board for ISRA communication subsystem with design hardware and software to meet the mission requirements which execute telemetry data transfer function as well as have our CubeSat transceiver designed by Sudanese researchers.

1.5 Methodology

The main issue of ISRASAT1 is to convey beacon signal and telemetry data between CubeSat and ground station, to complete this mission UHF transceiver will designed after determine the suitable height and optimal transmitted power, link budget must be designed between space segment and ground station depend on the frequency used, antennas gain, and sensitivity of the ground station receiver. However, Components will be selected under specific selection criteria to meet ISRASAT1 requirements and develop a special board for CubeSat communication subsystem after implement a good survey for available instruments.

Also, antenna system will be designed as a part of communication subsystem in addition software tools will be used for design and analysis. Two Software programs may be used for transceiver design, Advanced Design System **ADS** for mixer design and High Frequency Structural Simulator **HFSS** for antenna design.

1.6 Research Layout

This thesis divided into five main chapters, Chapter One provides the introduction of the topic and states the problem also introduces project challenges and proposed solution with its methodology.

Chapter Two contains the general overview of the small satellites combined with some explanation of CubeSat including ISRASAT1 project subsystems.

The Third Chapter discusses the wireless link and CubeSat transceiver, in this chapter link budget was explained with its equation, also a general survey was done for transceiver components and design means have been discussed in details.

The Final design of transceiver presented in Chapter Four, as well as more technical discussion of results with aid of simulation graphs and figures considering ISRASAT1 specification standard.

Chapter Five summarized the main ideas and conclusions offered by this investigation, along with the considerations of research and what could be done in the future.

Chapter Two: Overview of Cube Satellite

2.1 Background

The main purpose of CubeSat projects is educational, so the desirable mission must be simple and easy to do, however the life time of the space segment is very short upon on the nearest of orbit because the effect of atmospheric drag and space radiation. e.g. By the lifetime predictions of a CubeSat that turns on Low-Earth orbit it will not be exceeded three months [2].

Generally small satellite considers as alternative solution of traditional satellites because of reducing the cost by using Commercial off the Shelf COST component, no need long time to accomplish it, ability to use in various applications (such as exploration, imaging and remote sensing).

Despite all benefits that mentioned previously, there are some challenges most face the designer while selecting the fitted component because of limitation of size, Wight and power.

This constrains comes from CubeSat standard which restrict the size which does not exceed one liter (10x10x10 cm) of volume for one unit and 1 kg of mass with the opportunity to merge two or three units together to reach up to 30 cm^3 (30x30x30 cm) of volume and 3 kg of mass.

The main problem is the limitation of power because of using small battery size and very light to ensure that there are no any problems in CubeSat standard so the power consumption parameter must take under consideration during the selection of components.

2.2 ISRASAT1 Overview

ISRASAT1 is an educational project focuses on achieve CubeSat prototype as phase one project to inter the participations into research work by distrusted them in different teams, the team of ISRASAT1 divided into six teams every team has a unique mission.

Each team has a team leader who authorized for planning, distribute tasks and follow up the percentage completion of plan execution by reports.
ISRASAT1 CubeSat consists of six subsystems there are: OBC, Payload, Communication, EPS, Structure, and ADCS subsystem [**3**].

All teams lead by the ISRASAT1 project manager who is responsible the coordination between all teams and carry out some administrative burdens and financial facilities related to the project with the approval of the director of ISRA institute.

The Institute of Space Research and Aerospace (ISRA) launched ISRASAT1 CubeSat project in March 2015, subsequent to approved by Scientific Council of the National Center for Research (NCR) and funded by the Ministry of Finance.

The research plan of project is to design and implement the imaging system as a payload and send the beacon signal with passive control system to complete the prototype as phase one project, then design and implement the flight module with active control system and more efficient subsystems.

2.3 CubeSat Subsystems

There are many specifications must be taken under consideration along the design process such as orbital determination, inclinations, type of payload, frequency range, power budget, size and weight.

To realize the previous specifications, most of small satellites divided into many subsystems will represent and detail in this chapter, any subsystem has a team that responsible for put appropriate specifications to meet main mission, select suitable components and design own board for this subsystem.

In this thesis, Communication subsystem is a scope of research including all the work have been done to complete subsystem design such as requirements, specifications, calculations and simulations for CubeSat transceiver.

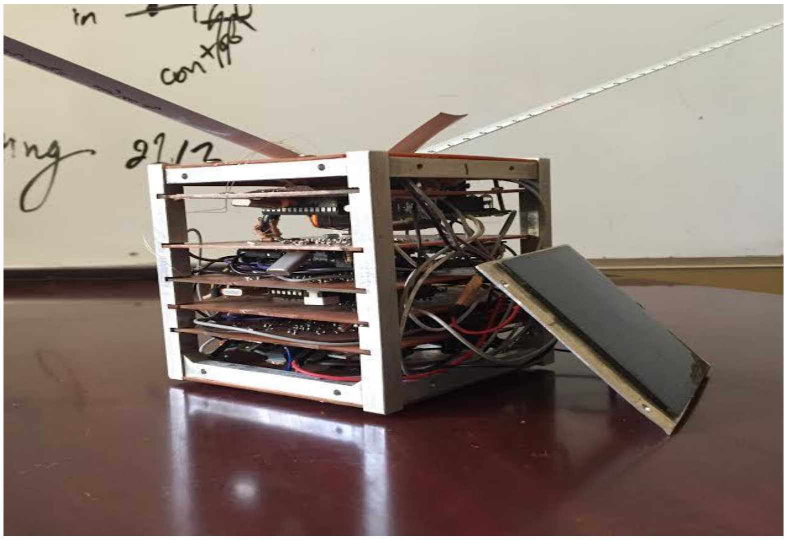


Fig 2.1 ISRASAT1 Prototype integrated Subsystems

2.3.1 On Board Computer OBC Subsystem

On Board Computer OBC subsystem is consider as the mind of CubeSat, it is responsible for connecting all subsystems using bus interfaces such I^2C, UART or SPI, also communication link control and data Collecting, in addition to RF switching between transmit and receive antennas.

For ISRASAT1 project, OBC is in charge to formatting data collected by ADCS and payload subsystems and send it toward communication subsystem to be able for beginning the transmission operation.

Software algorithm and hardware has been designed and implemented successfully to complete its own functions which designed for, software flow chart which explains the OBC algorithm is presented below in Fig 2.2**[4].**

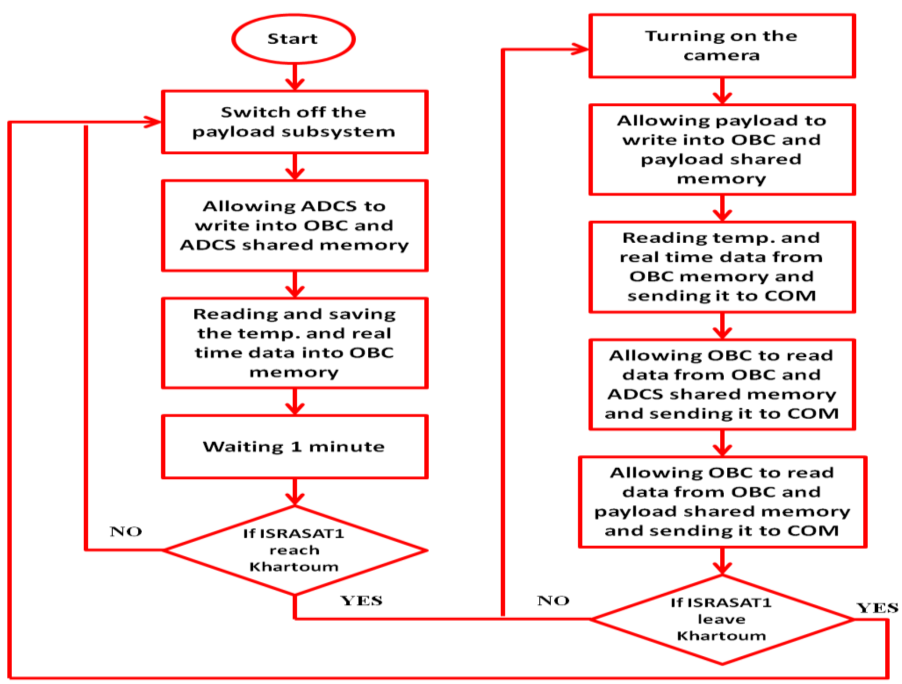


Fig2.2 OBC Algorithm Flow Chart for ISRASAT1

2.3.2 Payload Subsystem

Actual mission usually belongs payload subsystem, often it consists of environment sensors, camera or GPS, although the similarly of most CubeSat mission but it may be unique by creating new idea for payload.

Payload is the essential subsystem that make the cube sat designer to creating overall system; hence the failure of payload system means that completely failure.

In ISRASAT1 phase one, low-resolution camera for earth surface imaging have been selected to take some shots of Khartoum city as the main mission of payload. In phase two, imaging of clouds with a monochromatic sensor chip will be introduce as an evolution of phase one camera, payload shown below in Fig 2.3 **[5].**

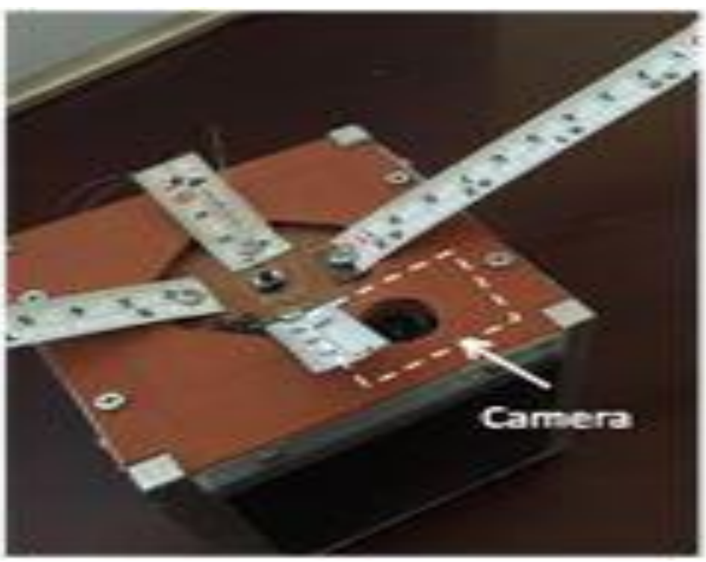


Fig2.3 Payload Camera of ISRASAT

2.3.3 Structure Subsystem

Because of special environment in outer space cube sat structure must have strong specification of material to be compatible with harsh climate, also size and weight constrains should take under consideration while manufacturing other subsystems boards.

For ISRASAT1 structure, the suitable material selected to meet the design requirements hence the hardware of CubeSat body implemented and absorbed all subsystems successfully inside the structure frame. More software tools used to simulate the frame structure and analyze the performance of structure e.g. solid work, major analysis test, final design of ISRASAT1 meets the CubeSat standard with 10x10x11 cubic cm as volume and 733.7 gram as total weight, Fig 2.4 shown ISRASAT1 Mechanical Structure frame and Table 2.1 illustrate weight budget of each subsystem **[6].**

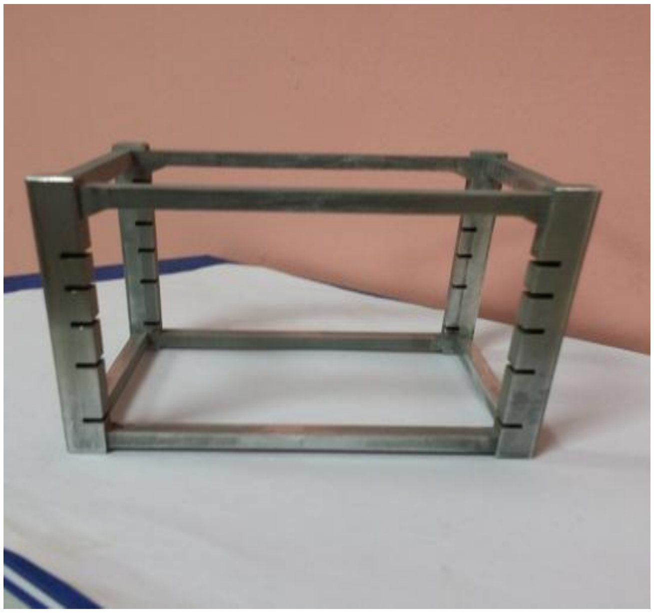


Fig2.4 ISRASAT1 Mechanical Structure Frame

Table2. 1 ISRASAT1 Weight Budget

subsystem	Weight (g)
ADCS	80
EPS	140
COMM	160
OBC	160
PS	300
Structure	200
Total	1040

2.3.4 Electrical Power Subsystem EPS Subsystem

Electrical power subsystem EPS is a central unit provides sufficient power to all subsystems and flows up all power consumption operations such as RF transmission and power amplification. In addition, it considers as a protection unit to avoid over current faults that may affect electronic components of other subsystems. EPS in any satellite is consisting of battery system, buses, solar panels and controller.

In ISRASAT1 project, EPS system designed carefully to deliver accurate values of voltage and current to all subsystem without missing the priority control and limitation of power, weight and size. Table 2.2 shows power consumption for each subsystem **[7].**

Table2.2 ISRASAT1 Subsystems Power Consumption

Subsystem	Voltage (v)	Current (mA)	Power(W)
OBC	5	214	1.07
ADCS	5	245	1.22
COM	3.3	568	1.87
Payload	5	100	0.5
Total	-	-	4.66

2.3.5 Attitude Determination and Control ADCS Subsystem

Attitude determination and control subsystem is responsible for determining the actual attitude to orientate the flight segment into correct orientations at three axes to point the antenna and imaging system toward the earth depend the ground station coordination. Attitude control accuracy is considering as important issue for antenna gain and directivity.

ADCS may use active or passive methods to maintain accurate attitude, in most satellites actuators uses as active devices to correct the orientations after determine error in attitude using determination algorithms.

In the first version of ISRASAT1, passive control used with two types of permanent magnet, which placed on CubeSat structure to exploits the magnetic field of the earth and minting the attitude. ADCS subsystem move toward a higher stage to be active control, as a development from the previous version and it will have deployed at ISRASAT1 phase two.

To develop active version, the design and implementation of Attitude determination and control subsystem have completed, also the selection of component such as magnetometer, Sun sensor, gyroscope, GPS receiver and microcontroller has done by appropriate criteria. ADCS will show below in Fig 2.5 **[8].**

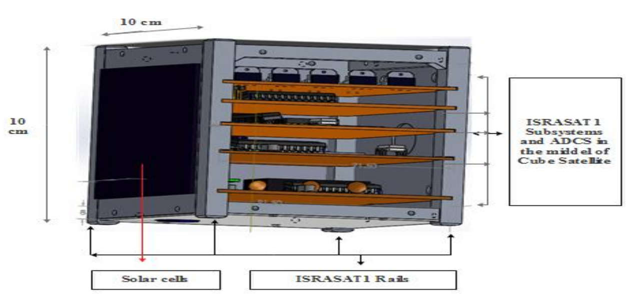


Fig2.5 ADCS in The Middle of CubeSat.

2.3.6 Communication Subsystem

The main function of communication subsystem is creating wireless link between space segment and ground station for handle tracking data (GPS), telemetry and command signals (TT&C).

Most of communication subsystems were consist of two separated transceivers one of them for beacon signal and another one for telemetry data. As known in small satellites, there are two transmission modes beacon and telemetry.

Beacon is a digital data commonly coded in Morse code techniques and modulated by CW analogue carrier. The massage sends by beacon transceiver usually content of the satellite name, the provider and the battery case. Most of the UHF / VHF (70cm and 2m) ground station used by amateurs supplied FM/AM to receive continues wave from small satellites. The CW signal transmitted each two or four minutes so the beacon line must be in active mode in order to provide an opportunity for amateur stations to receive beacon signals while the cube sat turning around the earth.

Telemetry is a digital data maybe contain GPS, sensors and actuator data that collected by OBC and modulated in digital scheme to send it over UHF link upon demand. to save power, telemetry transceiver should be in sleep mode even receives signal from OBC side Often the transmitter (digital data) is turned on when the satellite entering in ground station zone, the protocol used is AX.25 for split data and put it into appropriate template with transmission rate between 1200 to 9600 baud.

In first generation of ISRASAT1, two separated boards have been introduced as a communication subsystem, each one has own PCB (printed circuit board) and achieve different mission. The main mission of beacon is to provide link between the CubeSat and ground station to send beacon signal with message, which carry some status and identification information for tracking with own ground station or other amateur ground station, this message may be standard or customized, Fig 2.6 shows blocks diagram of beacon board **[9].**

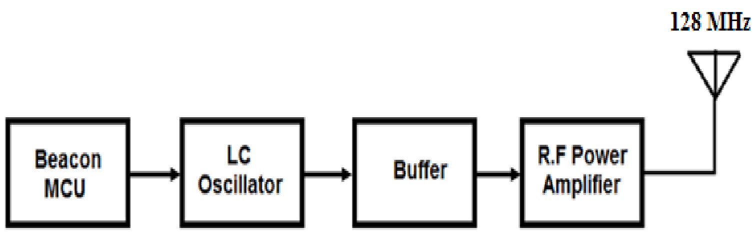


Fig2.6 Beacon Transmitter Block Diagram.

To complete CW Beacon mission VHF transceiver (128 MHz) have been designed and integrated with microcontroller unit (MCU) to generate Morse code message and form it as CW analogue signal, also have-wave dipole antenna designed and implemented to work at 128 MHz with 1.114 meter of length, Table 2.4 illustrate specifications of Beacon transceiver [**9].**

Table2.3 Specifications of Beacon Transceiver

Parameter	Value
Transmission mode	CW mode
Carrier frequency	128 MHz
Antenna length	1.114 m
Modulation type	FM
WPM (Word per Minute)	16
Data rate	45.5 bps

ICOM-2000 FM receiver used to receive CW signal with dipole antenna, it connected to personal computer PC in order to decode the Morse code data by using HamScope software, and Fig 2.7 shows Beacon Data Decoded Using HAMScope Software **[9].**

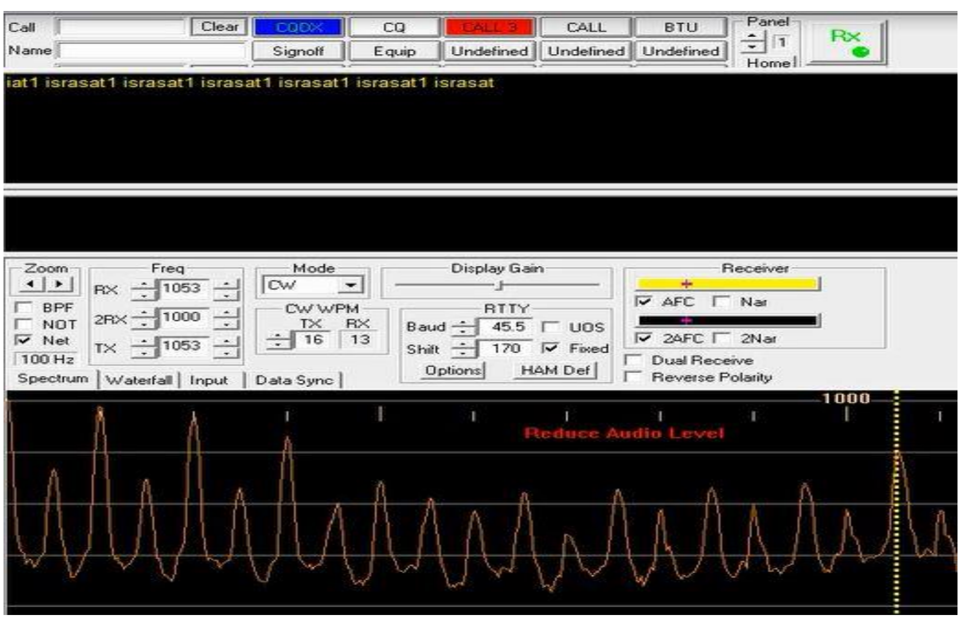


Fig2.7 Beacon Data Decoded Using HAMScope Software

In the second part of communication subsystem, data radio transceiver (UHF 868 MHZ) has used as telemetry and data receiver to send image captured by payload camera upon on OBC. In addition, half-wave dipole antenna designed and implemented to work at 868 MHZ with length of 0.164 m. Fig 2.8 shows ISRASAT1 Communication Subsystem General Block diagram and Table 2.4 illustrate specifications of data radio transceiver **[9].**

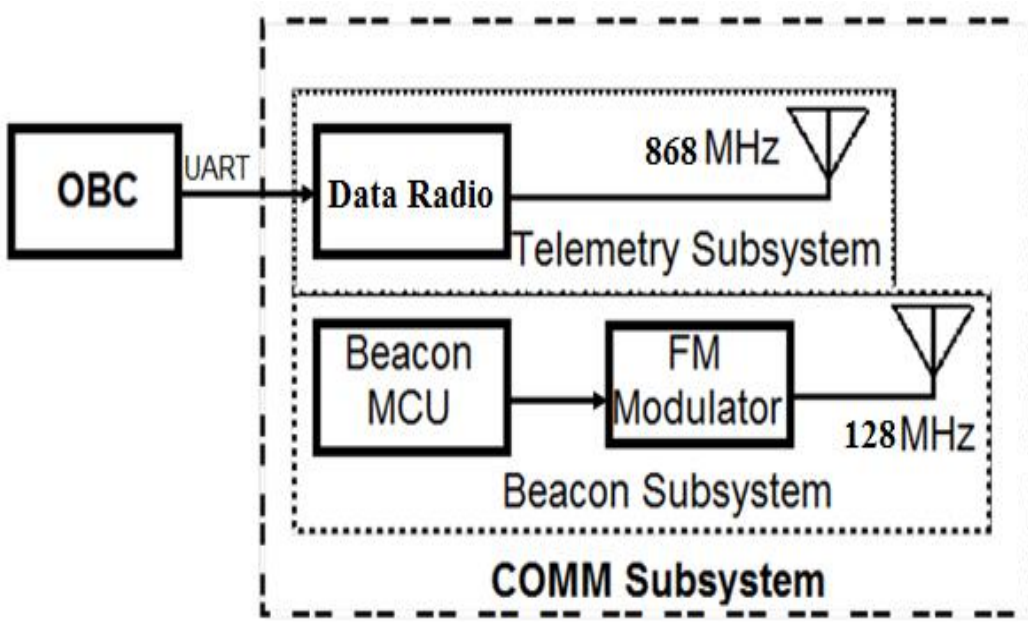


Fig2.8 ISRASAT1 Communication Subsystem General Block Diagram

Table2.4 Specification of Data Radio Transceiver

Parameter	Value
transmission power	1W
Carrier frequency	868 MHz
Channel rate	4800 bps
modulation mode	GFSK
Transceiver conversion time	<20 ms
Antenna length	0.164 m

ICOM-2000 FM also used to receive telemetry and data of camera as well as test the final work. The overall communication subsystem was working successfully after integrated with OBC unit and others subsystems, Fig 2.9 shows ICOM-2000 FM Receiver **[9].**

Fig2.9 ICOM-2000 FM Receiver

Chapter Three: Communications Link and CubeSat Transceiver

3.1. General Requirements

Any cube satellites have a specific requirement that is to handle information between satellite and ground station with low power signal using beacon or telemetry. Hardware and software design depend on the primary specifications such as type of payload, amount of transmitted data, transmission period, power budget, orbital selection and frequency range [1].

To set up a wireless transmission link for any satellite, link budget calculations must be the first step before starting the hardware design, to test the performance of the wireless link between satellite and ground station. In addition to, determine the quantities of gains, losses, and fade margin.
After link budget of all gains and losses had calculated the transceiver unit should be designed depend on the specification of the satellite and its budget of power [2].

The Link budget calculation process will be presented in details in this chapter with more explanation for main parts of small satellites transceiver's as a communication unit.

3.2 Link budget Calculations:

Link budget is a way to show the performance of communication links and determine the suitable power that can be received by the ground station; the link budget should be calculated for the link between transmitter and receiver **[10].**

Considering transmitter power P_t, transmitter antenna gain G_t and transmitter loss L_t, free space loss L_{fs} , loss margin L_m, receiver antenna gain G_r, and receiver losses L_r, the received power P_r can be obtained using equation (3.1) as follows:

$$P_r = p_t + G_t - L_t - L_{fs} - L_m + G_r - L_r \quad (3.1)$$

The free space loss can be calculated for distance d (Km) and frequency f (MHz), using equation (3.2) as follows:

$$L_{fs} = 20\log_{10}(d) + 20\log_{10}(f) + 32.44 \quad (3.2)$$

The receiver should have sensitivity less than power received obtained from equation (3.1). As long as receiver sensitivity selected below P_r, the reception will be optimum **[11].**

As known free space loss, significantly engaged with distance and operating frequency (wavelength), so the designer must be careful during the selection of link parameters because it is an unbearable process. Equation (3.3) demonstrates the relationship among free space loss, distance and frequency**.**

$$L_{fs} = 20log(\frac{4\pi df}{c}) \quad (3.3)$$

Additionally, to get values that are more rain that are more accurate, rain attenuation and other losses could be add into link budget equations as minus values.

3.3 CubeSat Transceiver

There is no different between traditional and small satellite transceivers in case of functionality, unless small satellites have low power and size.

In usual CubeSat transceiver, consist of several main parts such Terminal node controller (TNC), modulator/demodulator unit, power amplifier, matching circuits and antenna system. Fig 3.1 shows General block diagram of CubeSat transceiver.

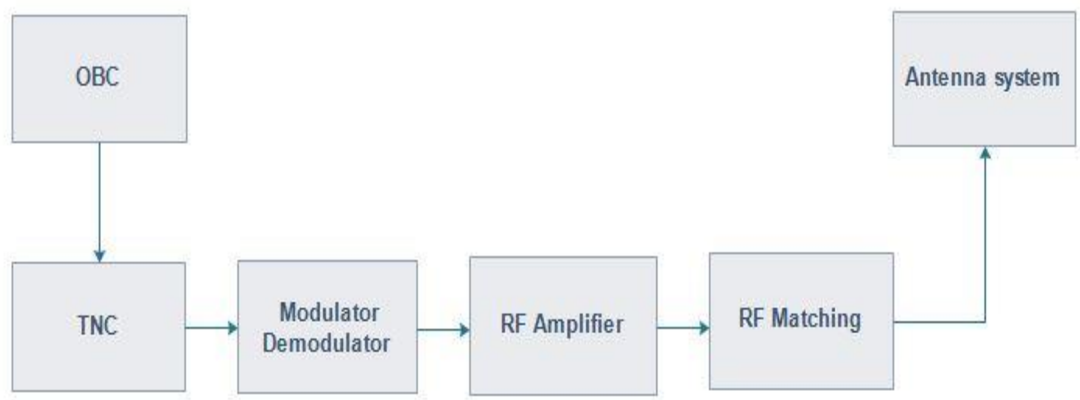


Fig 3.1 General Block Diagram of CubeSat Transceiver

3.3.1 Terminal Node Controller (TNC)

One of the tasks of TNCs is to convert data packets to audio tones, and vice versa. Most of ready-made transceivers have a built-in TNC, which allows using basic packet applications. Packet is a unit of data transmitted as a whole from one computer to another, on a network. Packets can be transmitted on radio waves as well as on communications lines. Besides a transceiver and a computer, all you need is a terminal node controller (TNC).

The TNC accepts data from processor (OBC) throw buses interface and assembles it into packets. It then converts those packets to audio tones, which the transceiver can transmit. In case of reception TNC also takes audio tones from the transceiver (modulator/demodulator), converts them to data for the on-board computer, and checks for errors in the data.

The protocol uses in case of data transmission throw wireless links over small satellites is AX.25 that split data and put it into appropriate template with transmission rate 1200– 9600 baud. TNC conform AX.25 protocol to allow radio amateurs handling packets between each other's using the same protocol over satellite communications link, it is consider as a data link layer protocol resulting from the X.25 protocol witch created to use by amateur radio operators and It is used widely on amateur packet radio networks.

The protocol could be customized or instead by another type such as Morse code in casing of beacon transceiver **[12].**

In usual, the TNC was a microcontroller such as a Microchip PIC or ATMEGA microprocessors interfaces with the transceiver to program register settings throughout set up the transmission stage. Table 3.1 shows some options of programmable chips uses as TNC.

Table3.1 Microcontroller (TNC) Options.

MCU	Speed	Voltage Supply	Current supply	Flash	EEPROM	Interfaces
ATmega 32 AVR	16 MHz	4.5-5.5V	200mA 400mA	32K Bytes	1024 Bytes	UART SPI-Serial
ATmega 16L AVR	8 MHz	2.7-5.5V	200mA	16K Bytes	512 Bytes	UART SPI-Serial
ATmega 16 AVR	16 MHz	4.5-5.5V	200mA	16K Bytes	512 Bytes	UART SPI-Serial
Arduino Uno	16 MHz	5V	50mA	-	1 KB	UART SPI-Serial

3.3.2 Modulator/Demodulator

This unit could be the main unit of transceiver because it consists of electronic circuits to achieve the radio transceiver functions, sometime called modem or radio transceiver. Some companies develop modulator/demodulator in a single unit known as transceiver on chip to make the designing and implementing process of CubeSat transceivers easier and faster for students, single chip transceiver performs well in VHF/UHF bands for small satellites purposes.

Common manufacturers for such chips comprise Texas Instruments, RF Micro devices and Analog Devices **[13].**

Astro-Dev and ISIS, starts providing ready-made radios intended for CubeSat but they have very high prices for limited funded projects that running into universities and institutes for educational purposes. Table 3.2 shows some type of transceivers with brief details.

Table3.2 Transceiver Survey Options.

UHF/VHF Transceiver	Provider	Transmit power	Modulation /baud rate	Sensitivity Rx	Interface Tx/Rx
CC1101	Texas instrument	+12 dBm	FSK/OOK 500 kbuad	-112 dBm	SPI
CC1000	Texas instrument	+10 dbm	FSK/OOK	-110 dBm	SPI
ADF7020-1	Analog-devices	+13 dBm	FSK/ASK 200 /64	−119 dBm	3 wire serial
RF2905	-	-	-	-101dBm	-
Bima2a	Radio-Metrix	10mw	FM (64kbps)	-101 dBm	3 wire serial
ATA5428	ATMEL	10dBm	FSK /20Kbps	-112.5 dBm	SPI
Custom	-	-	-	-	-

Universities often make a decision to build the whole transceiver by primary electronic components or went to modify a transceiver that Designed for use on earth below the CubeSat standard to minimize the cost instead of purchasing expensive radio for CubeSat.

However, the inability to provision single chip radio may diverse you resort to the previous solution as happened in ISRASAT1 project.

3.3.3 Power Amplifier Unit

Due to very long distance and using the lowest power components in communication subsystem of CubeSat, power amplification process should be introduced to add more gain for the transmitted and received signals. Amplifiers could enhance the output power at the satellite before transmit analog signal into wireless link that allows ground station to receive signals into accepted level. However, preamplifier uses at receivers to achieve amplification functions, received power and power sensitivity are important parameters which used to qualifying wireless link especially in satellite communications.

Some types of lumped elements such as Transistors could use as amplifiers, also single chip could use instead of lumped elements. Table 3.3 illustrates many types of amplifiers.

Table3.3 Amplifier Options Survey.

Amplifier	Supplier	Frequency range	Gain(400 MHz)	Operating voltage	Operating current
AH117	WJ Com	400-2200	30 dB	+5V	120 mA
AH312	WJ Com	400-3200	18 dB	+5V	800mA
RF2117	RFMD	400-500 MHz	33dB	3v – 5v	1200 mA
Custom	-	-	-	-	-

3.3.4 Matching Circuits

For radio frequency circuits and microwave devices there is main issue that affected the performance of transmitting signal by these devices which is reflect signals from mismatching load with the transmission line, reflected wave could make a defect on electronics component, matching circuit should be designed to equalize the characteristic impedance of transmission line $\boldsymbol{Z_o}$with load impedance $\boldsymbol{Z_L}$**.**

Equation number (3.4) shows the relation between reflection coefficient $\Gamma$and impedancesZ_o,Z_L**[14].**

$$\boldsymbol{\Gamma = \frac{Z_o - Z_L}{Z_o + Z_L}} \tag{3.4}$$

Matching circuit designed by lumped element or by adjusting the diminution of transmission line, most of RF circuits designed to perform 50-ohm impedance and it is preferable to operate with UHF/VHF transceivers.

There are several types of impedance matching such as:

- **Matching with lumped elements**
  This may be feasible for frequencies up to about 1 GHz; there are three possible configurations for this type L-section network, T-section network and pi-network. Fig 3.2 shows the different configurations of lumped elements impedance matching.

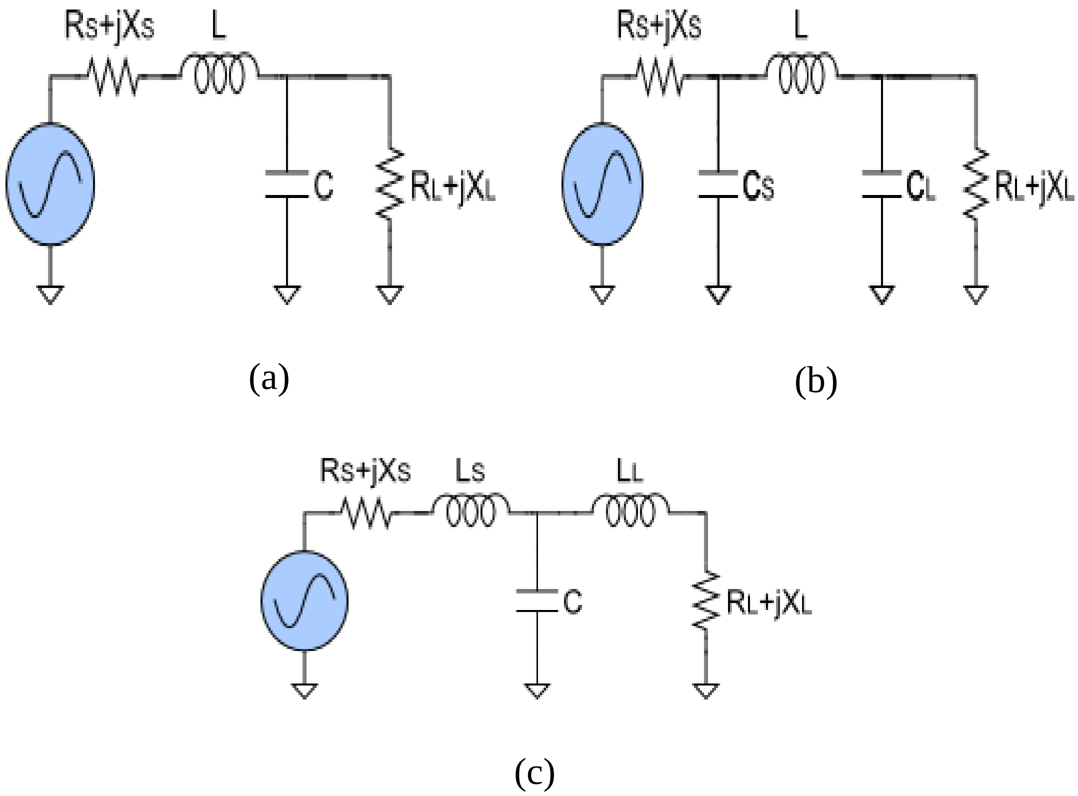


Fig 3.2 Lumped Element Matching Network. (a)L-section Network, (b) Pi Network, (c) T-section Network.

- **Stub tuning**

This may be feasible for frequencies above 1 GHz, the number of stub elements could be single, double or series. Stub depends on distance from source or load, fabricated material of stub (section of transmission line) and its dimensions (width and thickness). Fig 3.4 shows the different configurations of Stub tuning impedance matching.

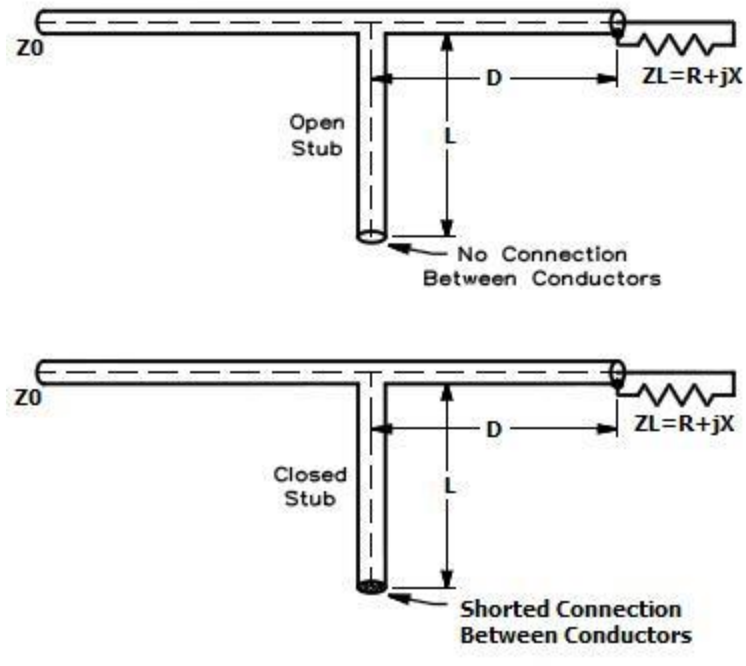
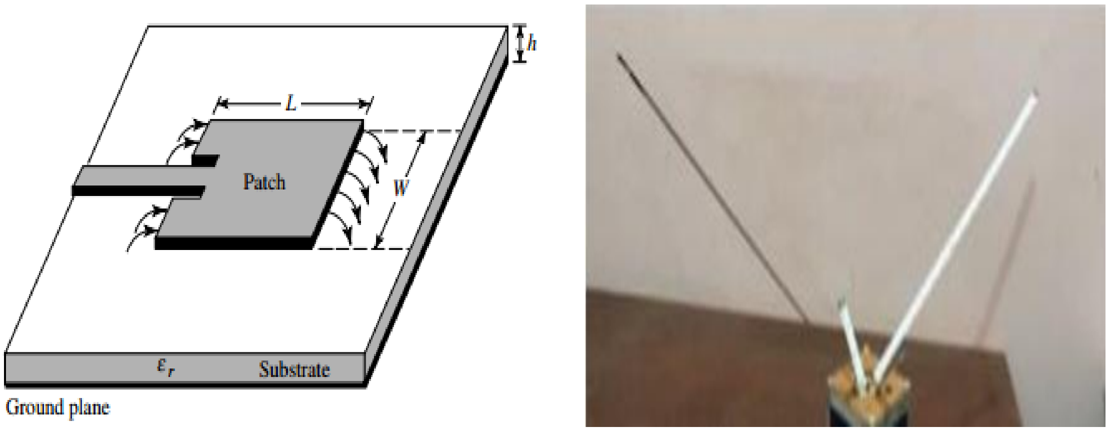


Fig 3.3 Single Stub Matching Network (short/open stub)

3.3.5 Antenna System

dipole antenna is considered as optimal choice while designing of antenna system whose belongs to CubeSat because the radiation pattern of dipole antenna is the nearest pattern of isotropic antenna. Omni directional antenna is commonly used in CubeSat at UHF/VHF bands in order to simplicity of tracking by ground stations.

Most communications subsystems of amateur satellites have been designed with whip antenna as recommended choice, also patch antenna used at wide bands of frequencies with high gain performance and directivity **[15].** Fig 3.5 shows different types of antenna used for small satellite applications.



(a) (b)

Fig3.4 Antenna Elements Types. (a) Patch Antenna. (b) Wire Dipole Antenna.

To complete beacon mission SSB-FM receiver could be used at the ground station, AFSK receiver is required to receive telemetry data with low data rata (1200-9600buad). Fig 3.6 shows the radiation pattern of dipole antenna, which designed for ISRASAT1 first version. Voltage stand wave ratio (VSWR) is an important parameter that should be taken into consideration during the design to minimize the amount of reflection wave and enhance the transmission performance.

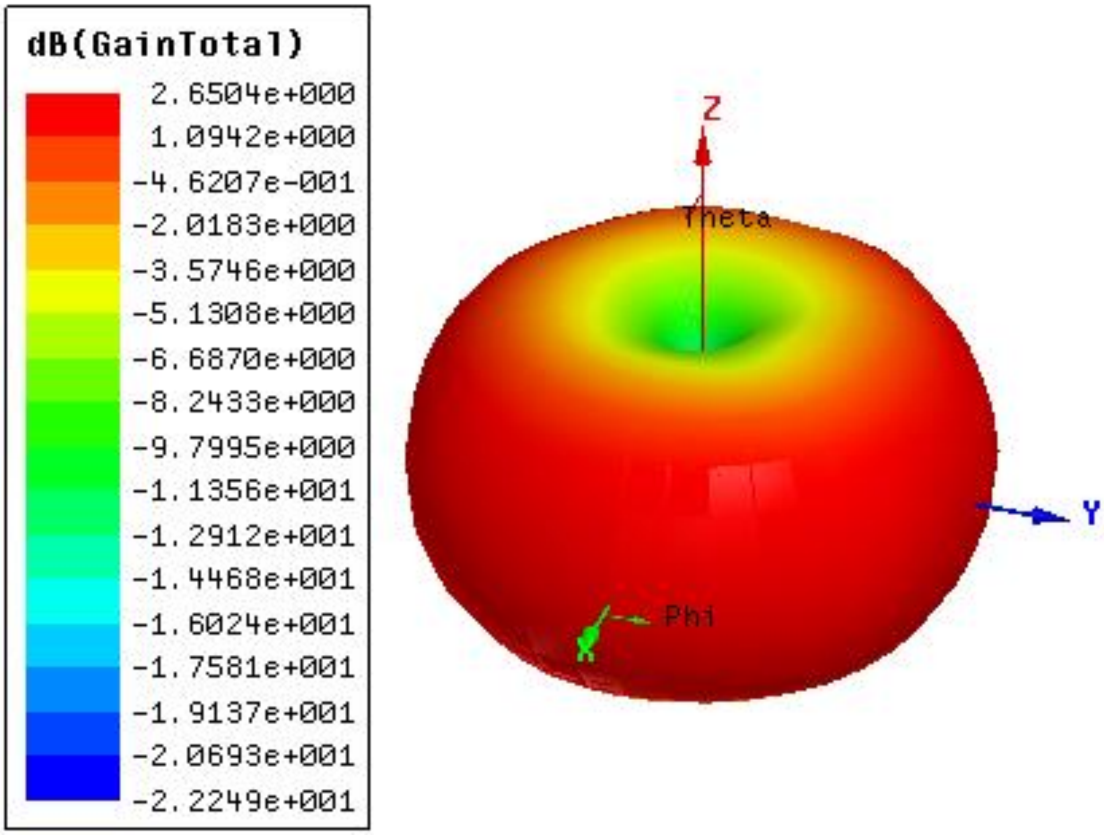


Fig 3.5 Radiation Pattern of Dipole Antenna.

3.4 ISRASAT1 Specifications

After complete fully investigate of general requirements about CubeSat communication link and transceiver design with good survey for components, the particular specifications of ISRASAT1 project had developed upon previous requirements as follows **[3]:**

- One-unit (1U) CubeSat prototype.
- 100mm Length.
- Mass don't exceed 1.33kg.
- Low-resolution camera to capture spatial images will be equipped.
- Turns on low earth orbit (LEO) of about 450km Altitude

- Inclination of 90 (polar)
- Two separated transceivers, beacon and telemetry.
- Downlink frequency (430-450MHz) for telemetry mode.
- Downlink frequency (133-137 MHz) for beacon mode.
- Half Dipole or monopole antenna
- AFSK- Modulation (1200bps-9600bps) for telemetry board.
- FM-Modulation (very low data rate) for beacon board.
- Half-duplex (both transceivers).

More design details will be presented in next chapter with aid of simulation features that could explain procedures, which had been followed during design process and analyzing the results. Also, selection criteria of components would be discussing.

Chapter Four: Simulation and Results

4.1 Background:

In this chapter, the design of communication subsystem for ISRASAT1 and the Simulation of its all parts that includes TNC, AFSK modulator, mixer, matching networks and antenna which has been chosen or customized to achieve the potential goals will be presented and discussed. Obtaining the desired research aims and analyzes the results after create a model of communication subsystem and using the most suitable settings of the system.

To achieve the previous methodology, CubeSat transceiver has been divided into several sections as a cascade, each section has its own parameters and results but it’s not independent from others. Fig 4.1 shows system design diagram of ISRASAT1 transceiver model.

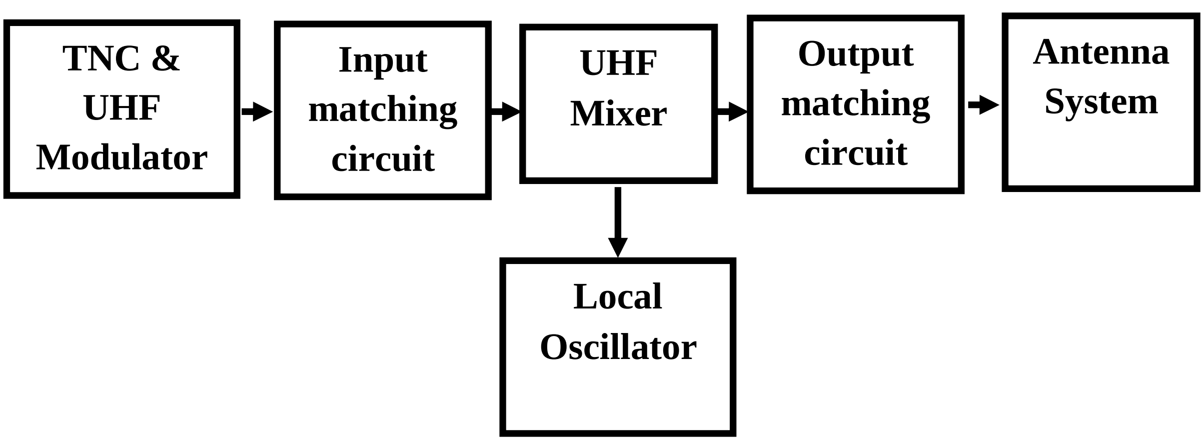


Fig4.1 System Design Diagram of ISRASAT1 Transceiver Model.

CubeSat transceiver designed based on different parameters using ADS, and HFSS CAD software. The main objective is to optimize the design to find the best configuration of the system that can operate at optimum performance to be implemented on the real system. This also can provide a clear picture based on results aid performance graphs of the designed configurations whether or not the design objectives can be achieved.

4.2 Design Specifications

Communication subsystem was designed to follow ISRASAT1 standard as shown in chapter three in this thesis. The specification used for this design as shown in Table 4.1.

Table4.1 System Design Parameters.

parameter	Value
IF frequency	2.2 KHz
RF frequency (operating frequency)	433 MHz
CubeSat altitude	450 Km
Modulation type	AFSK
Transmitted power	2 watts (33 dBm)
dimensions	(10x10x10) cm
Structure material	Aluminum

According to specifications shown in Table 4.1, link budget was calculated as shown in Fig 4.2. As shown in this figure to have gain margin of 11.21 dB, receiver should have features of -110 dBm sensitivity and 10 dBi antenna gain, hence transmitter should have minimum gain of 2 dB.

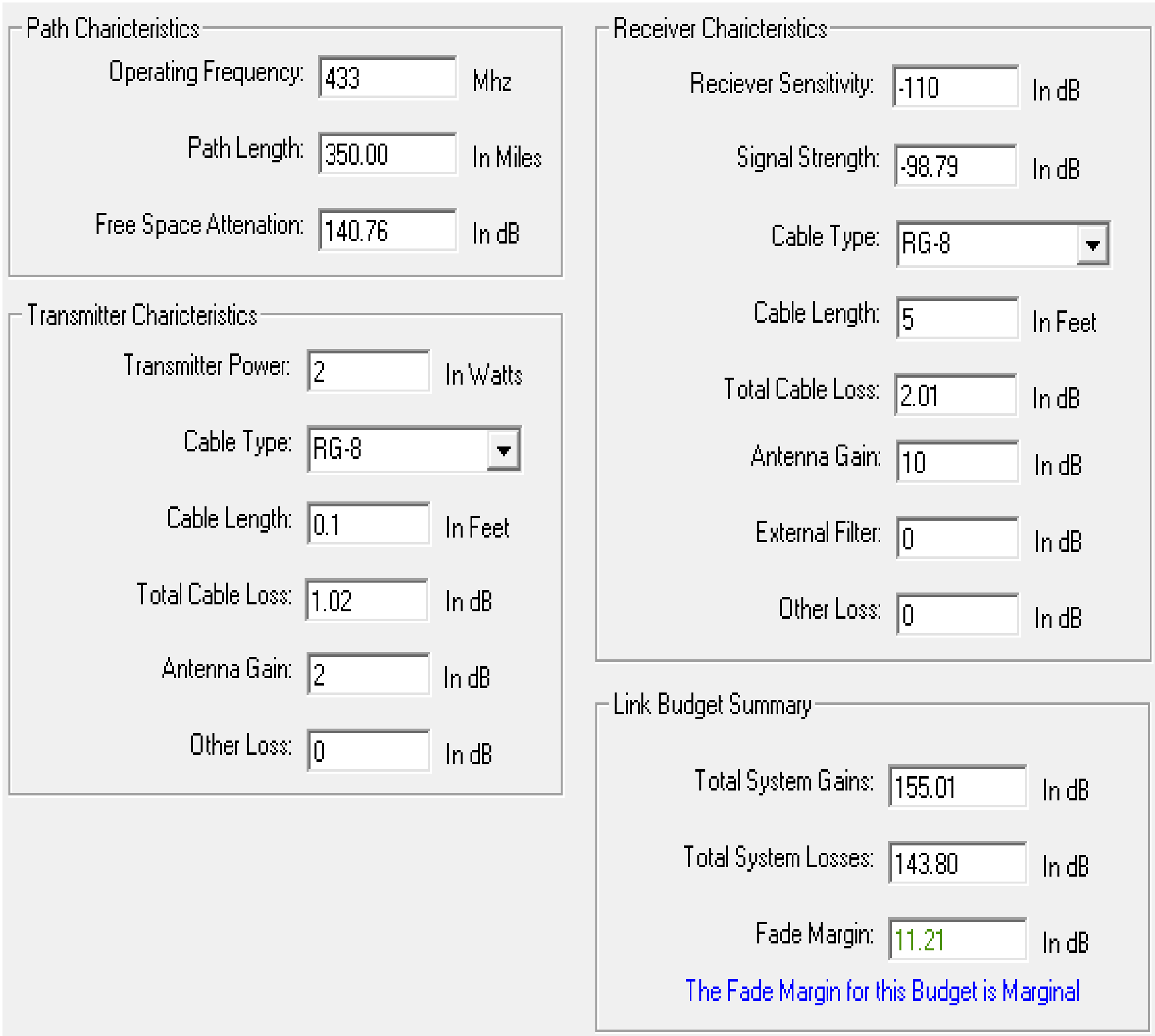


Fig4.2 ISRASAT1 Link Budget Calculations.

4.3 Terminal Node Controller Design

TNC system illustrated in Fig 4.3 as a functional diagram with AFSK modulator, they have been implemented using Arduino based system as shown in Fig 4.4**[16].**

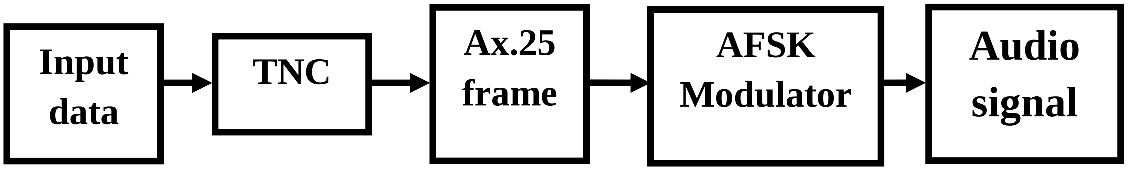
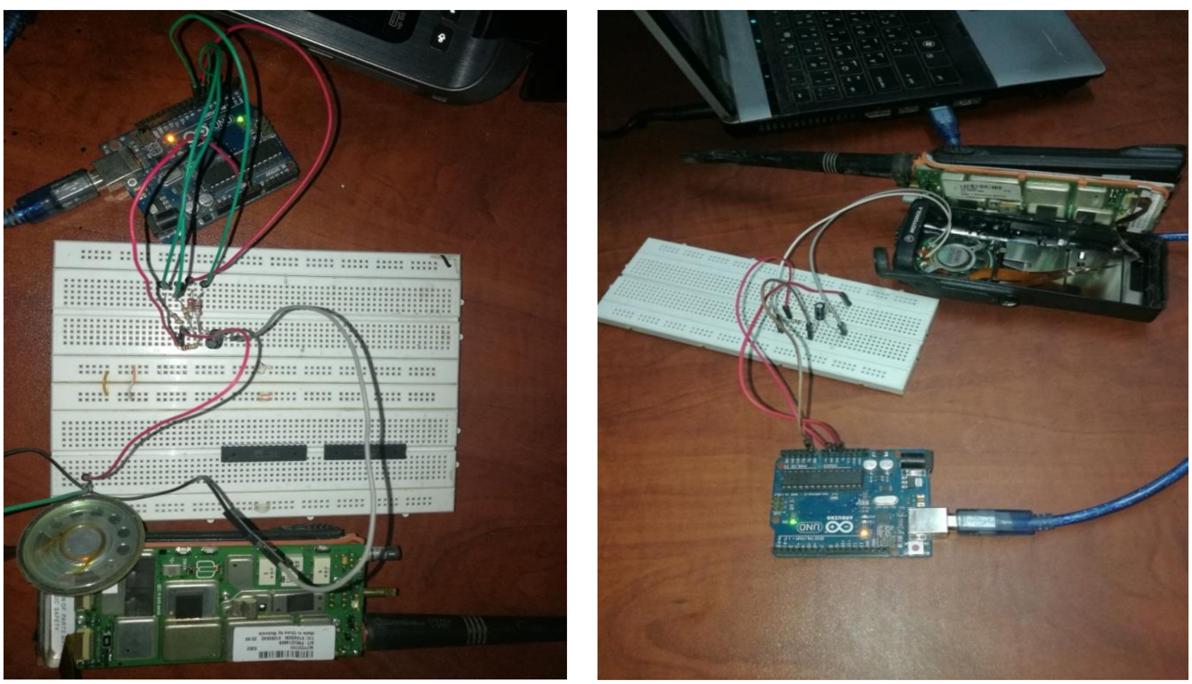


Fig 4.3 TNC and AFSK Functional Block Diagram

The transmitter consists of computer as data source, Arduino based system as TNC and AFSK modulator, and Walkie-Talkie to verify the analog transmission between Tx and Rx and AX.25 protocol has been implemented successfully.

The receiver has been implemented using Arduino based as well, with computer to receive the data transmitted; Fig 4.4 shows hardware implemented circuits.



(a) (b)

Fig 4.4 Hardware Implementation (a) Tx circuit, (b) Rx circuits.

The results obtained sending text from a computer and receiving the text in Different computer as shown in Fig 4.5 and Fig 4.6. Besides audio signals as spoke out from walkie talkie **[16].**

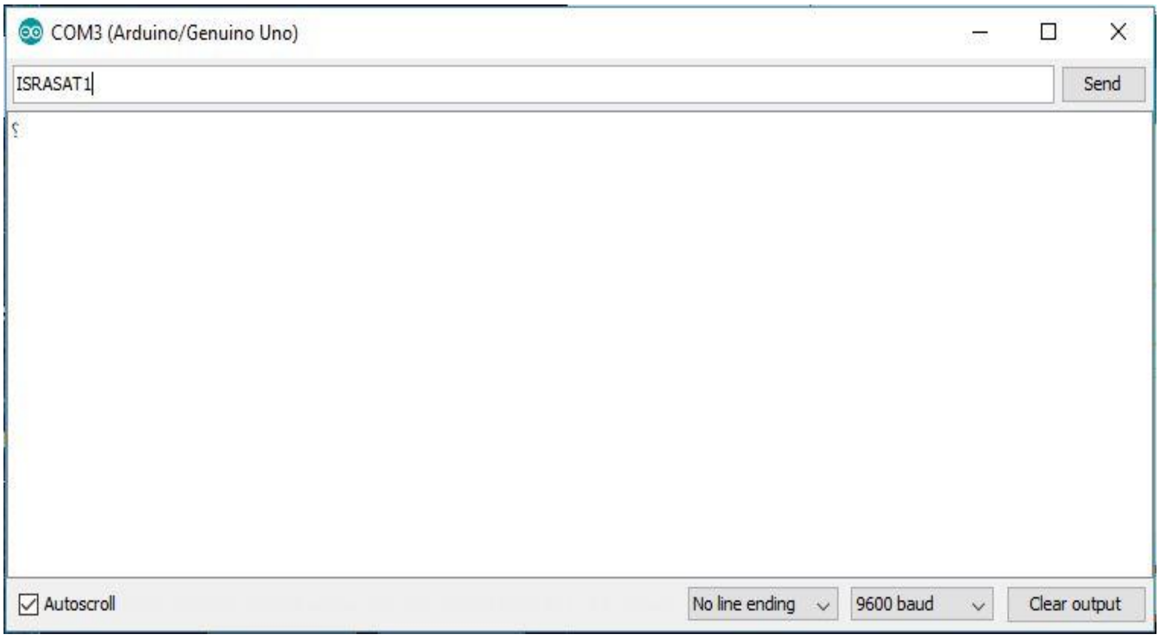


Fig 4.5 Transmitted data from computer A

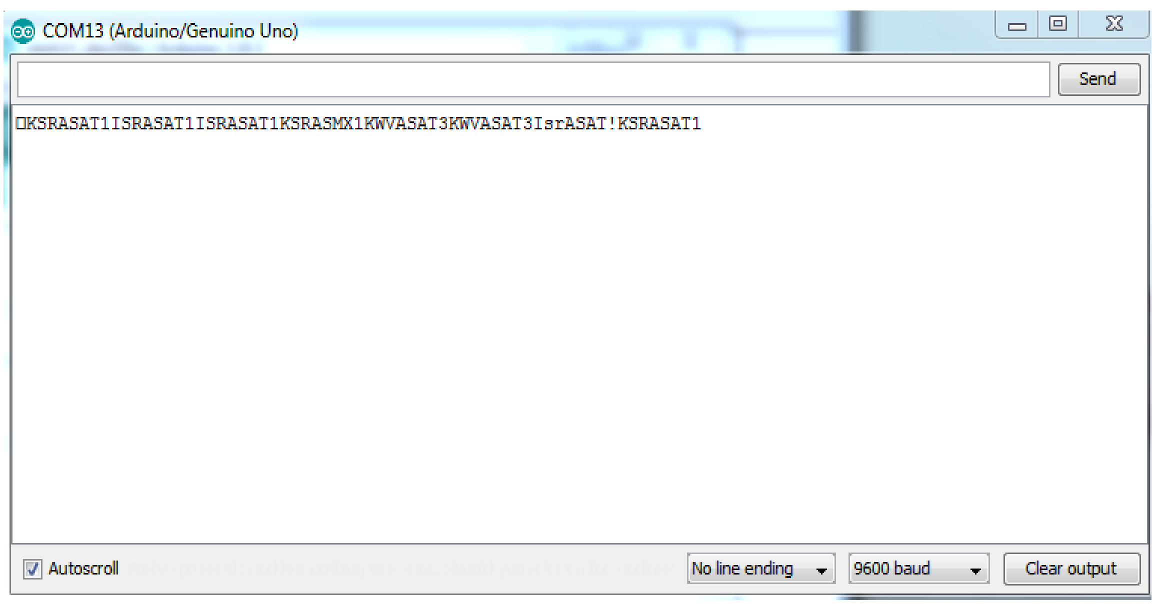


Fig 4.6 Received data at computer B

4.5 UHF Mixer Design

This section is designated to design a single ended transistor from lumped element (transistors, conductors, capacitors) as a BJT mixer in order to play a role of up/down frequency conversion, in this scenario simple UHF Mixer operating at 433.0 MHz is designed.

The IF signal at 2.2 KHz is up converted into RF frequency of 433 MHz, mixer takes the IF signal from modulator with 1200 or 2200 Hz then escalates it into RF form with 433 MHz .

The mixer is targeted to have low attenuation (conversion gain near 0dB) and an operating noise figure of less than 10 dB, the design steps are divided into 5 parts. These are the DC biasing of the mixer circuit, S-parameters measurement for RF and IF, input matching, output matching and final design verification. Fig 4.7 illustrates the designed mixer in ADS CAD using BFR92A BJT transistor.

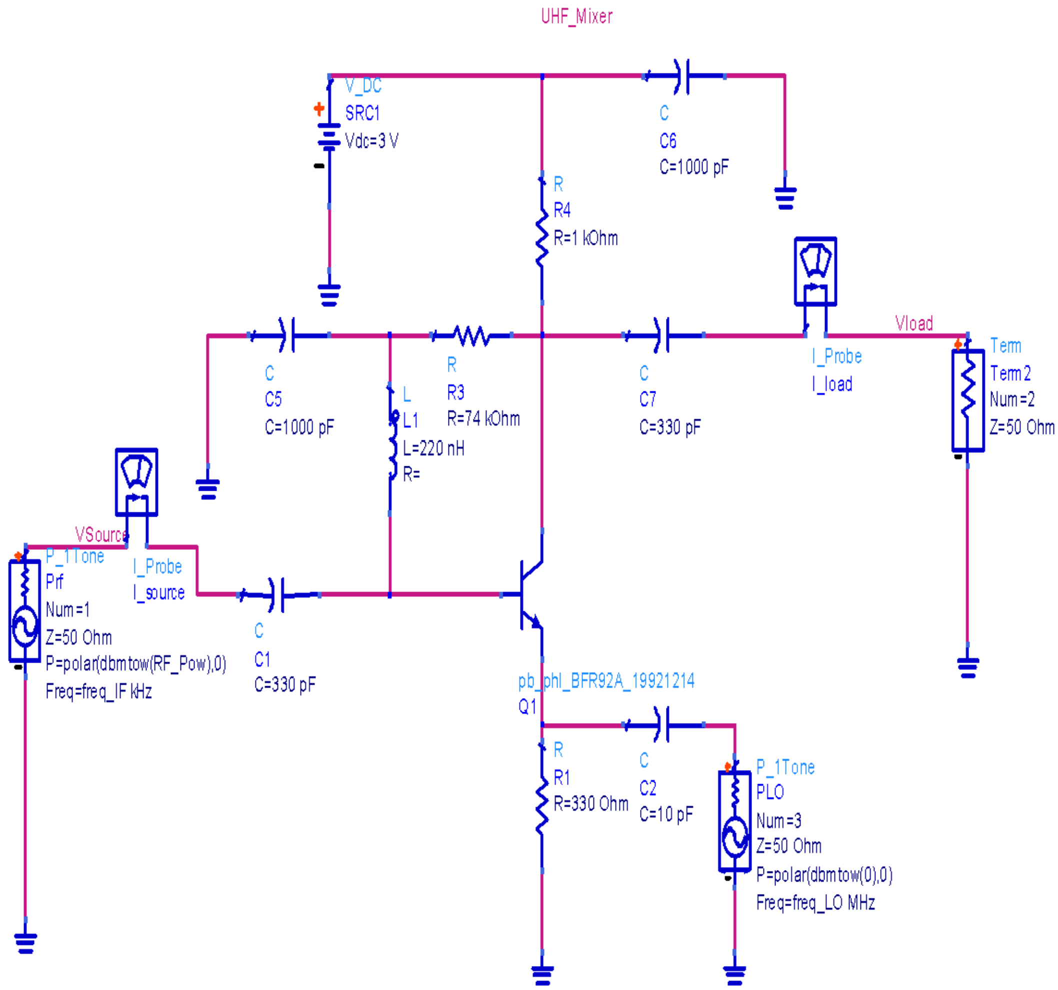


Fig 4.7 UHF Mixer without Matching Network

IF signal and RF signal spectrum as shown in Fig 4.8 and Fig 4.9 respectively, illustrating harmonic imbalance as 2.2 KHz IF signal has -13.9 dBm where the second harmonic has -10.9 dBm at the input of the mixer. Although at the output, there is harmonic imbalance, where the carrier 433 MHz has -10.9 dBm and the second harmonic of 866 MHz has -13.5 MHz, this imbalance occurs due to port mismatching with both source and load. Time domain illustration of source and load signals has been presented in Fig 4.10 and Fig 4.11 respectively.

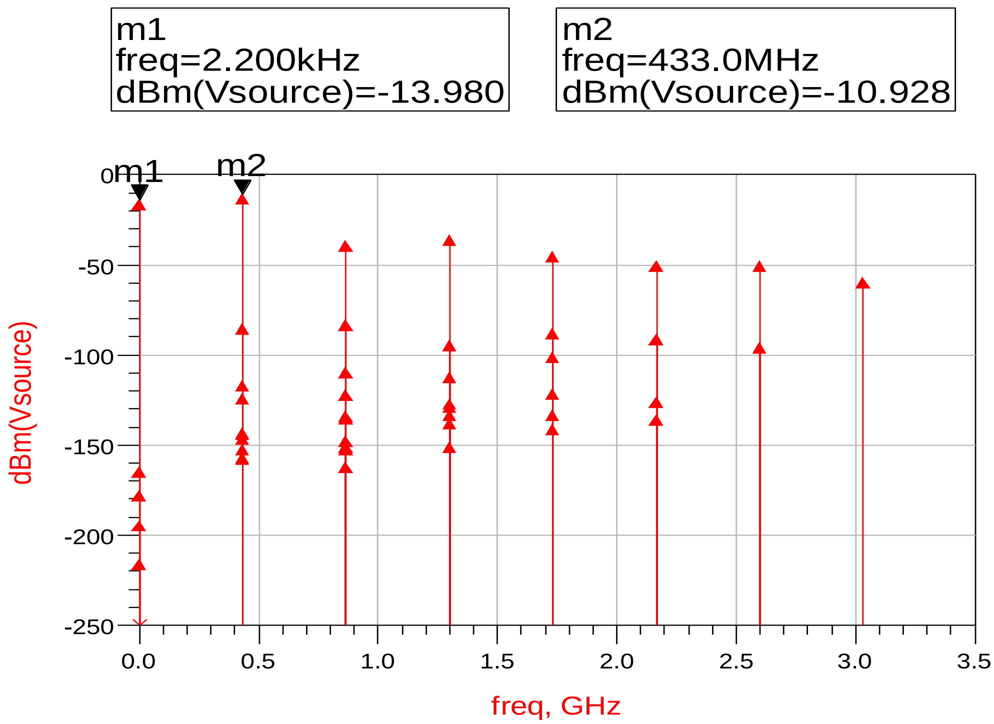


Fig 4.8 Source Signal Spectrum

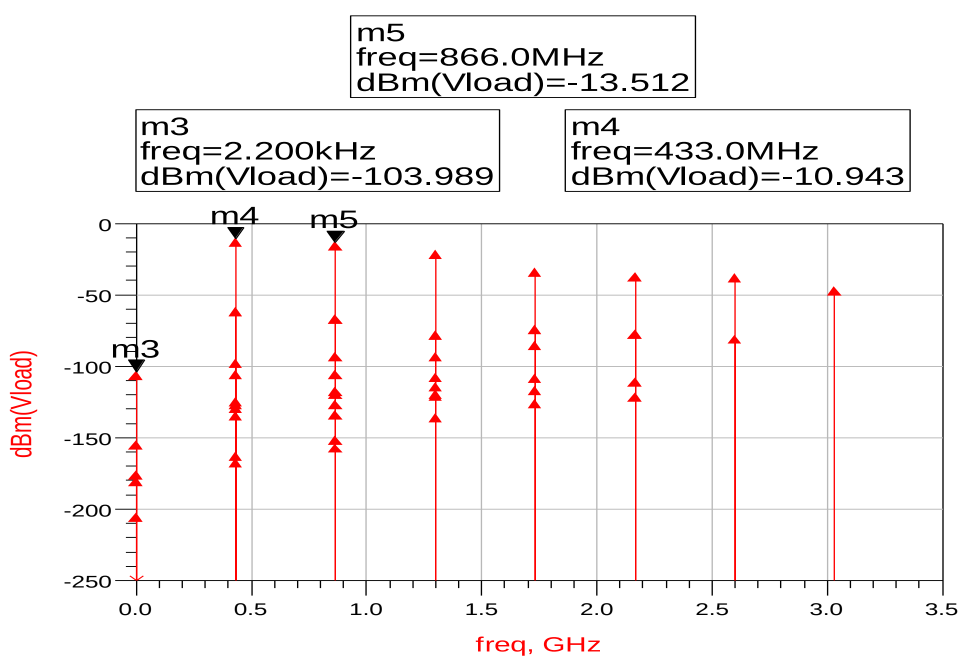


Fig 4.9 Load Signal Spectrum

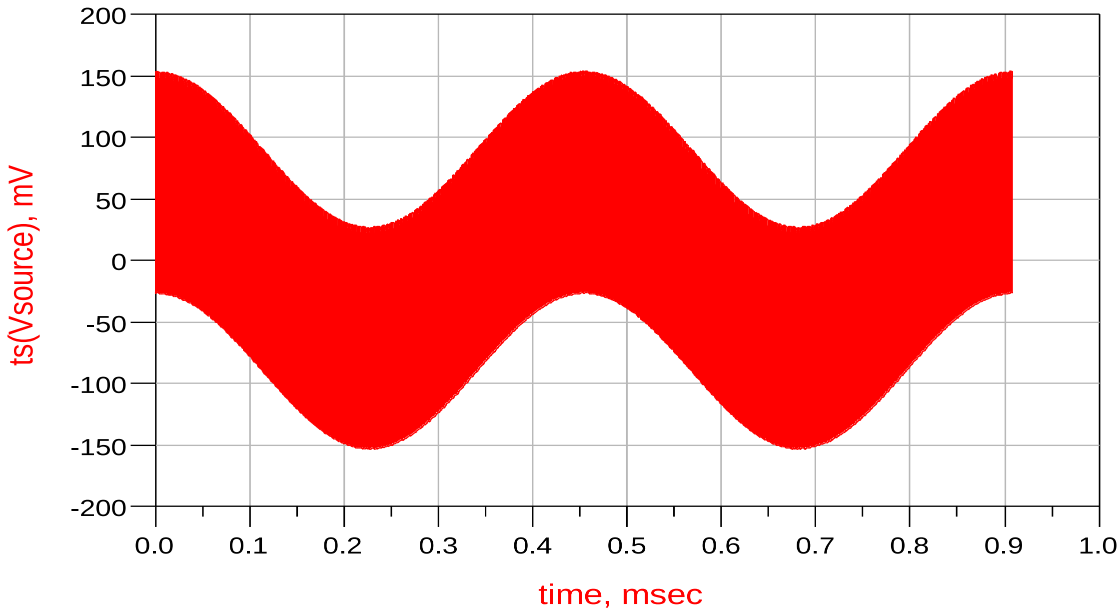


Fig 4.10 Time Domain Source Signal

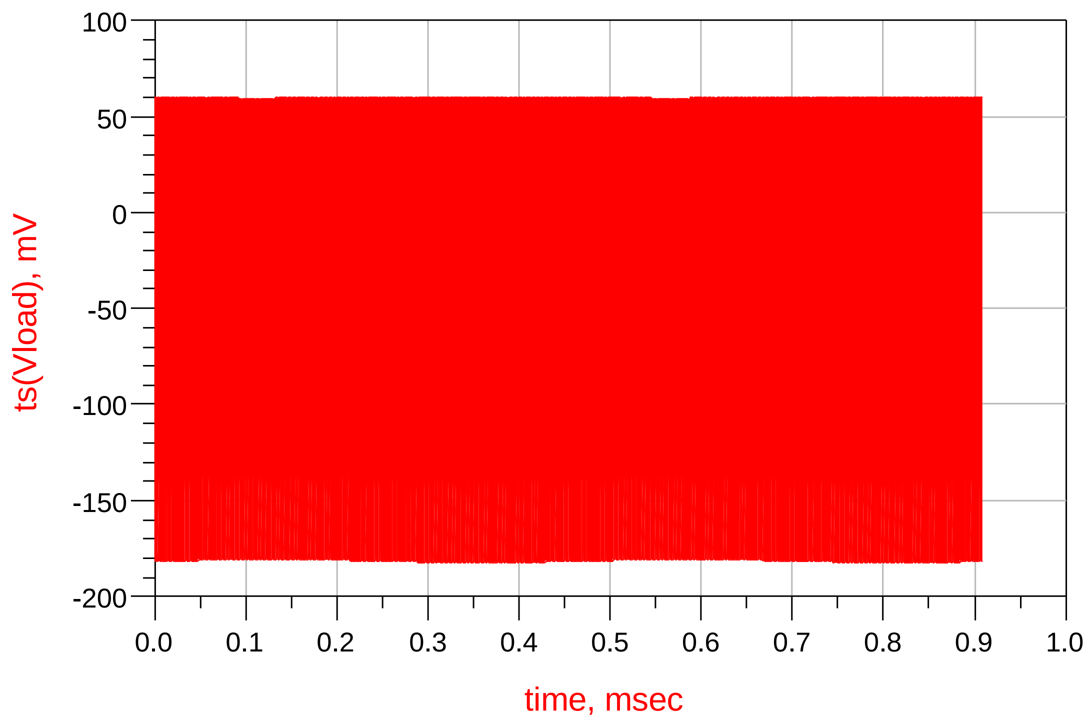


Fig 4.11 Time Domain Load Signal

4.6 Matching Circuit Design

To obtain better results at both source and load terminals a matching circuit is designed. Lumped element matching networks has been selected because the operating frequency is less than 1 GHz. At the source (input) port a PI network is designed to match a source of 50 Ω with mixer input impedance of 493.9-j44.02 Ω. An online tool [17] has been used to calculate the required values for capacitors and inductors. Fig 4.12 shows designed PI network using ADS. Moreover, L section matching network was selected to match 50 Ω load to the output of the mixer with 0.999-j1.123 Ω as shown in Fig 4.13.

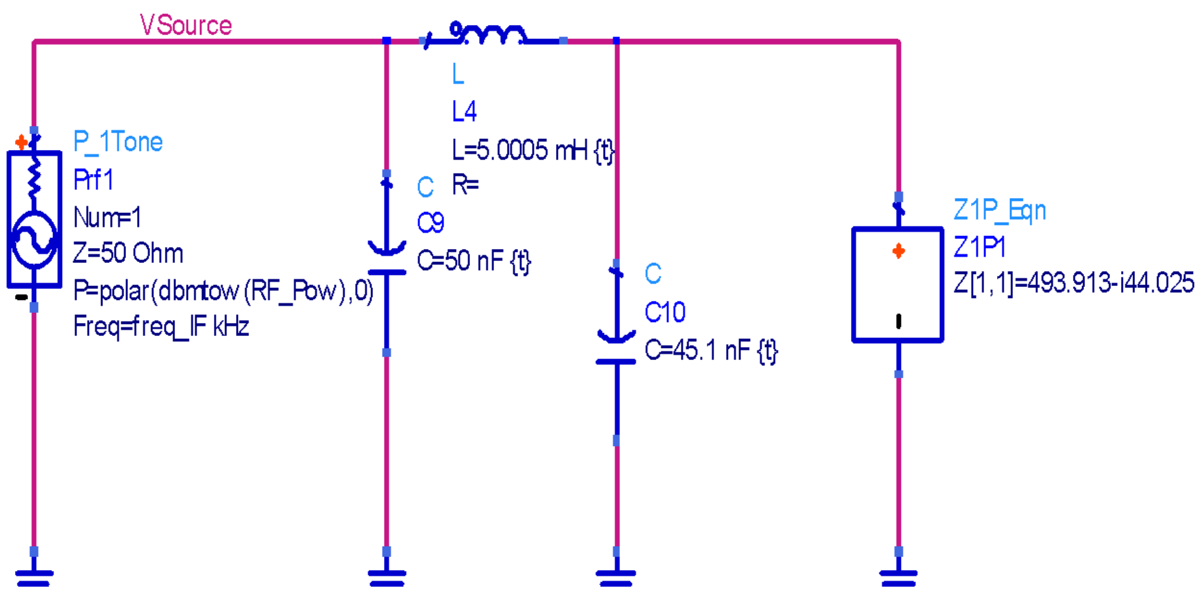


Fig 4.12 Pi Network Matching Circuit at Mixer Input

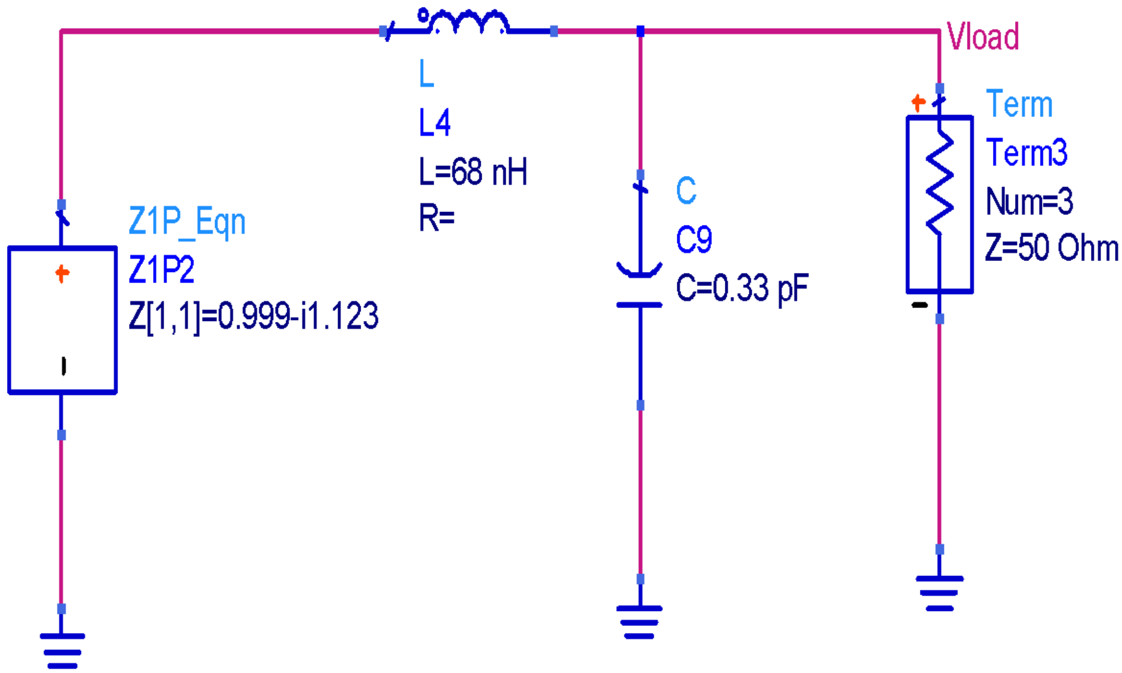


Fig 4.13 L-Section Matching Network at The Output of Mixer

Adding both PI and L matching network to mixer circuit, as shown in Fig 4.14 to enhance frequency stability of the mixer. The new design showed enormous enhancement in harmonic balance at the input port where the required frequency 2.2 KHz has -13.9 dBm and second harmonic has -270 dBm as illustrated in Fig 4.15. However, output port network did not improve harmonic balance much as shown in Fig 4.16. Time domain signal at the input port as shown in Fig 4.17, has one frequency compared to signal in Fig 4.10.

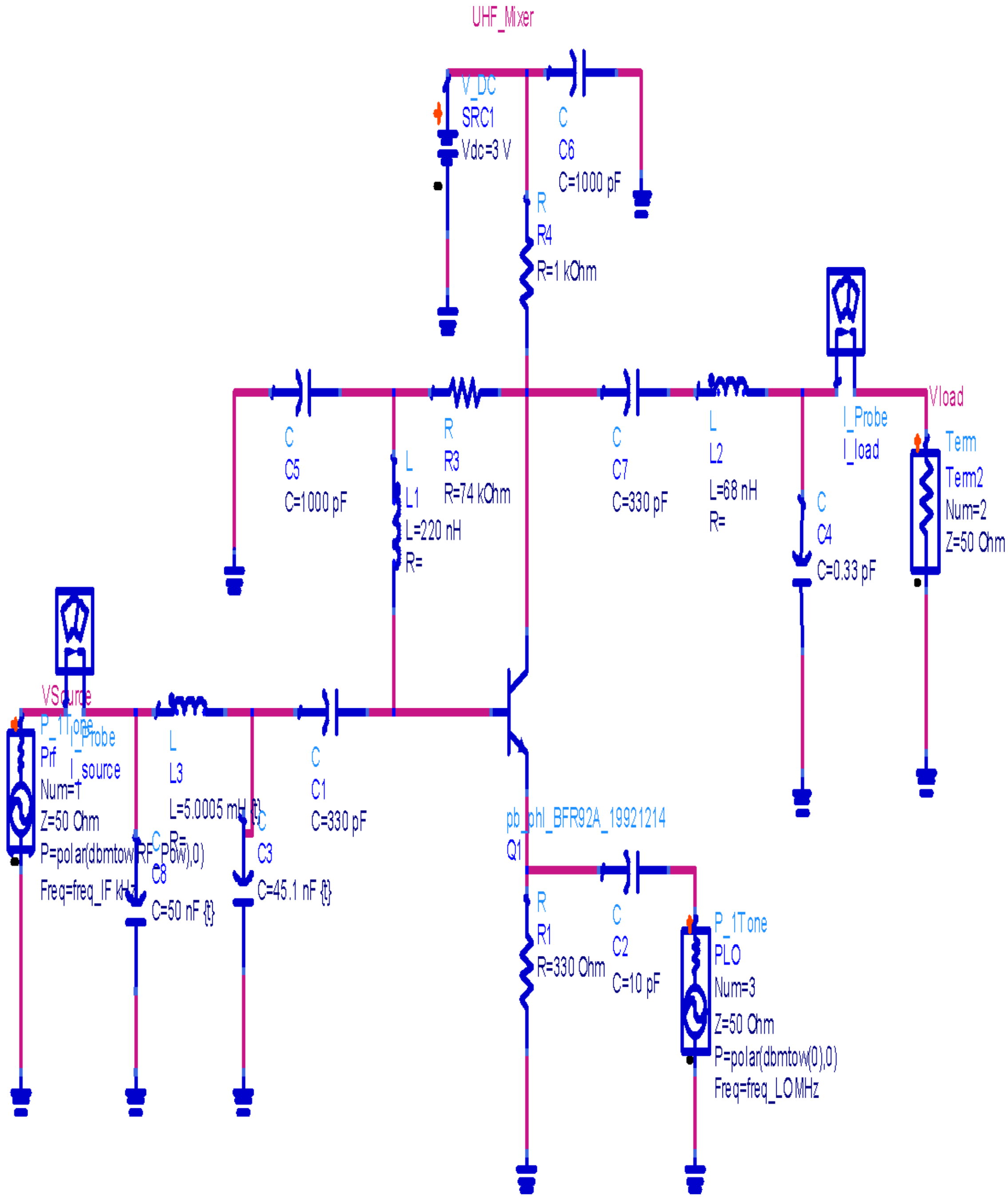


Fig 4.14 Mixer Circuit with Matching Networks

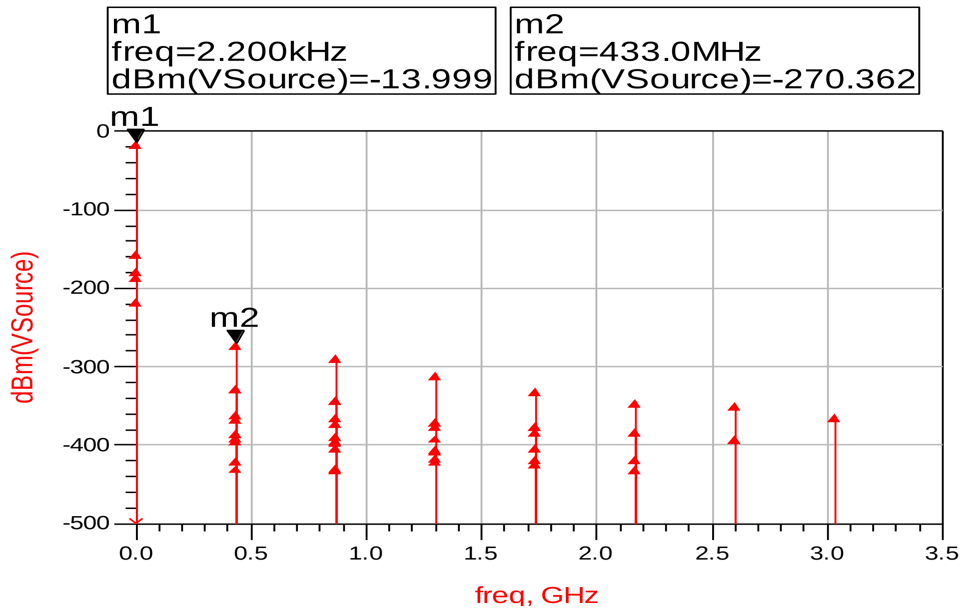


Fig 4.15 Source Signal Spectrum after Matching Network Addition

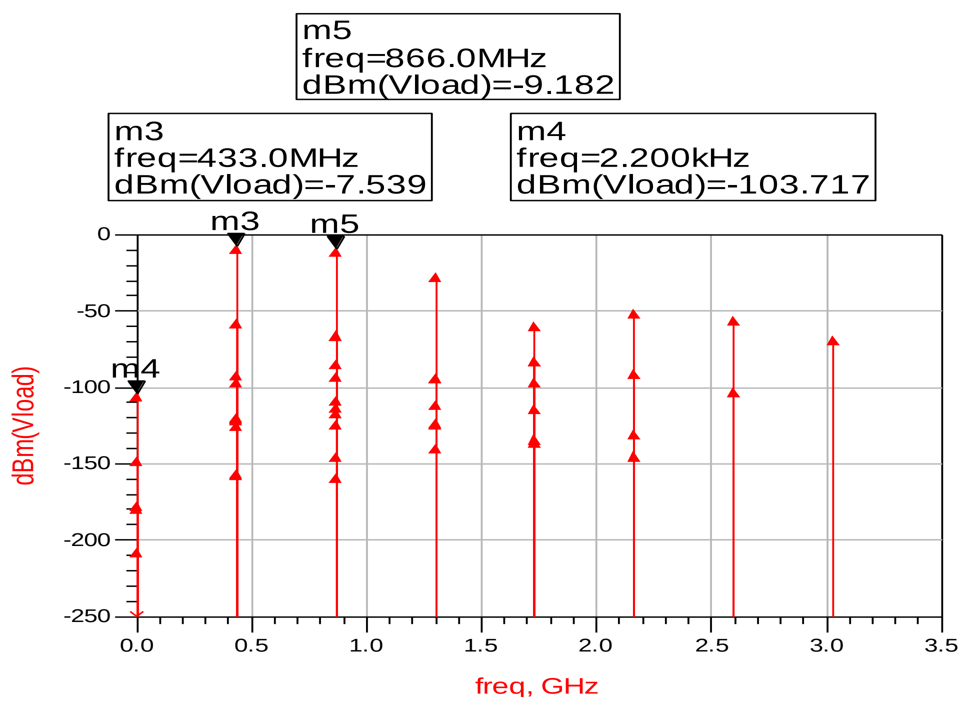


Fig 4.16 Load Signal Spectrum after Matching Network Addition

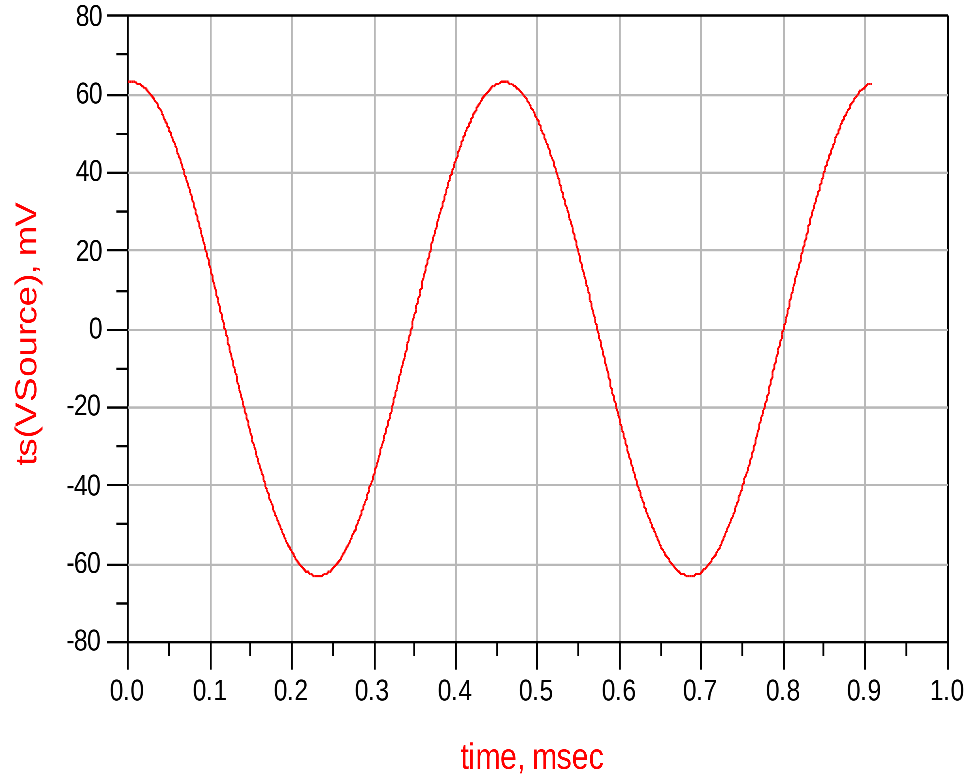


Fig 4.17 Time Domain Source Signal after Matching Network

To separate the second harmonic for the RF carrier, a Band Pass Filter BPF has been designed as shown in Fig 4.18. The filter frequency response illustrated in Fig 4.19, showing magnitude of 8 dBm at the RF frequency and -10 dBm at second harmonic with approximately -18 dBm gap.

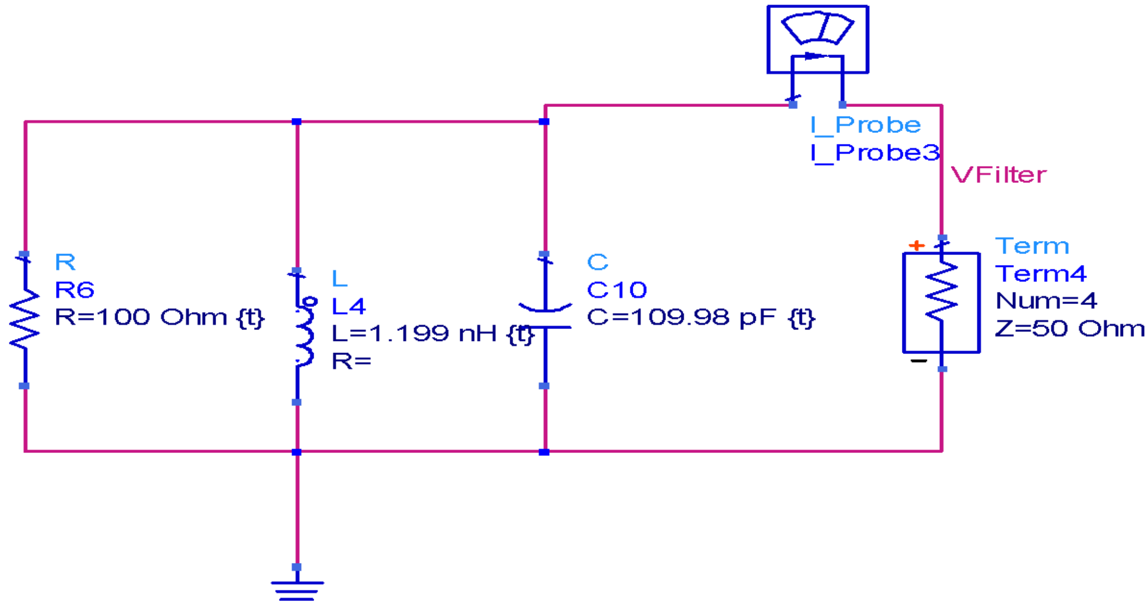


Fig 4.18 Band Pass Filter

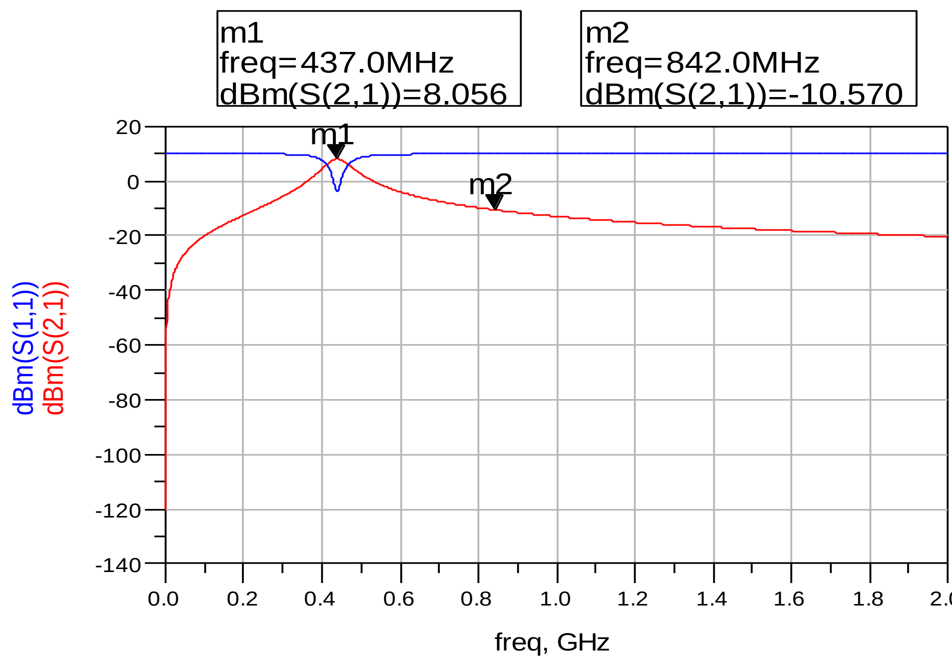


Fig 4.19 Designed BPF Frequency Response

Adding designed BPF to the mixer circuit as shown in Fig 4.20, obtaining results showed in Fig 4.21 which illustrated a good separation of second harmonic.

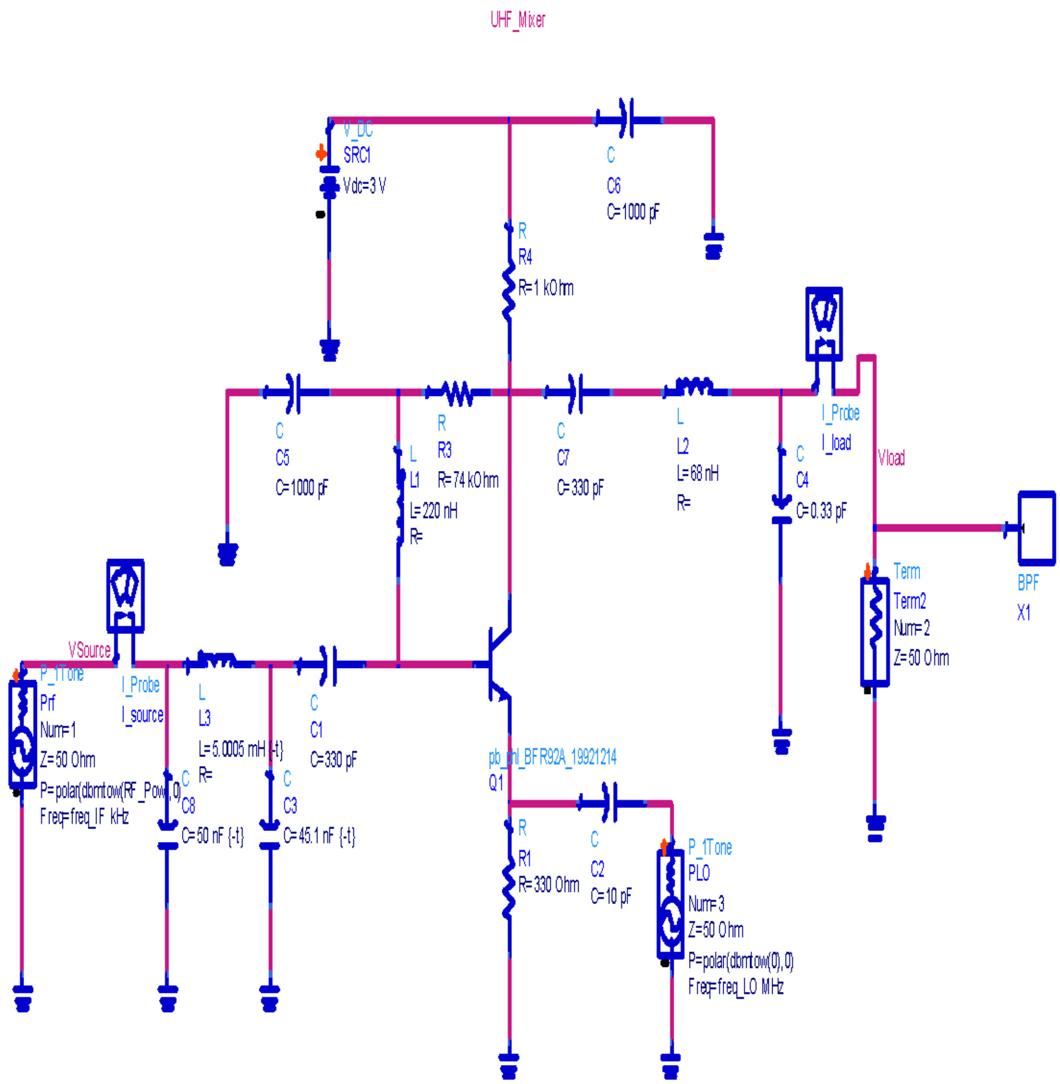


Fig 4.20 Mixer with Matching Network

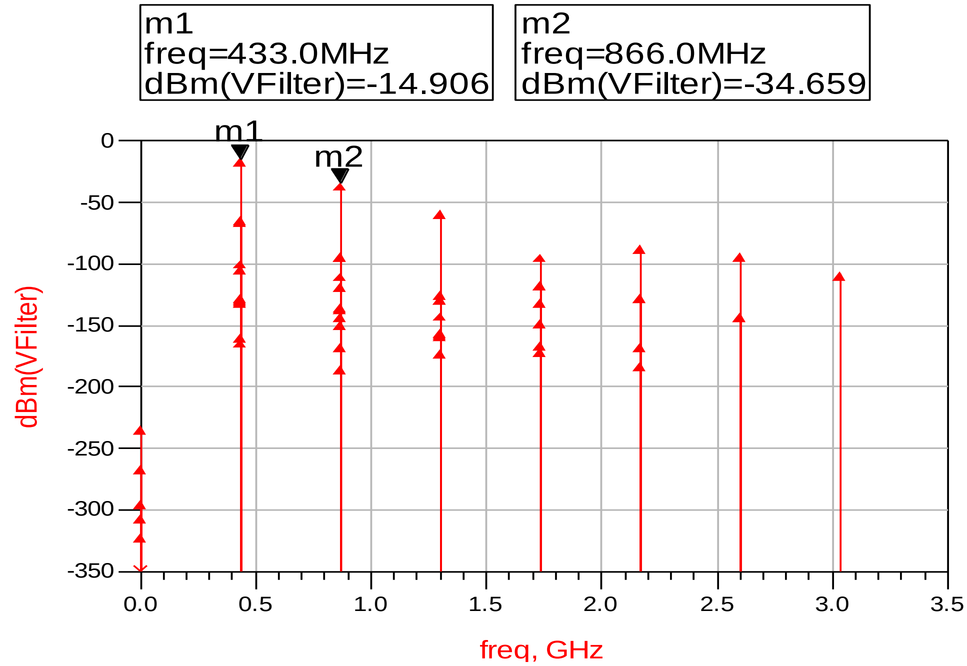


Fig 4.21 Load Signal Spectrum after using BPF.

4.7 Antenna System Design

Following ISRASAT1 standard in Table 4.1 and link budget in Fig 4.2 an antenna was designed to transmit the RF power. HFSS was used to design this antenna to operate at 433 MHz and has 50 Ω input impedance. Fig 4.22 shows CubeSat structure with the dipole antenna. The designed antenna appeared to have gain of approximately 3 dB as shown in Fig 4.23. Fig 4.24 illustrates polar plot of radiation pattern. Designed dipole antenna has VSWR equal to 3 at 433 MHz as shown in Fig 4.25 and insertion loss IL about -6 dB at operating frequency as shown Fig 4.26.

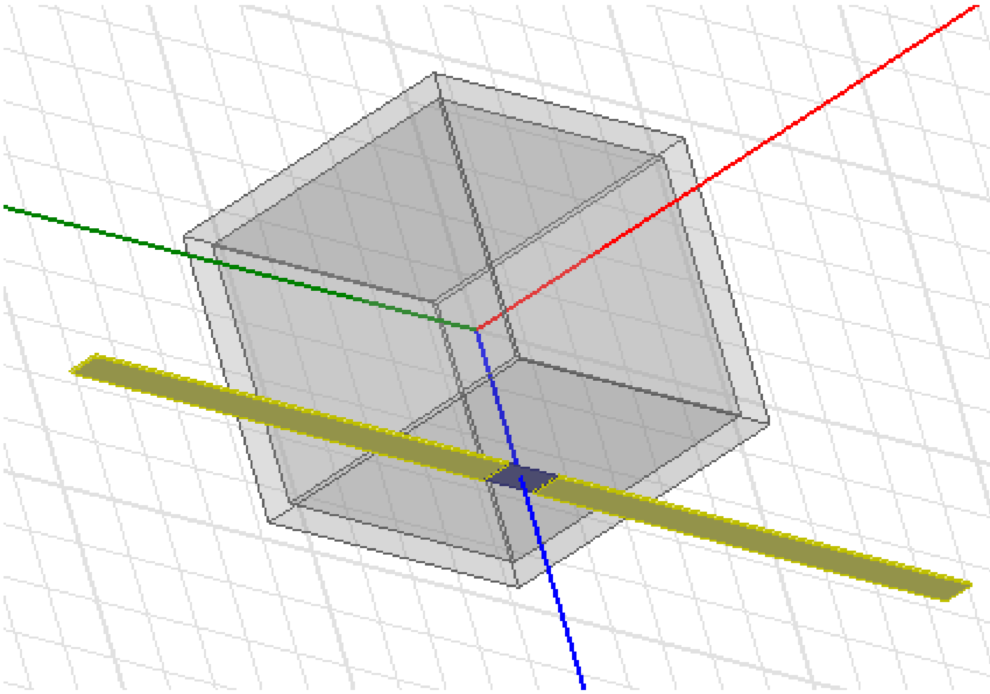


Fig 4.22 CubeSat Structure Model (HFSS).

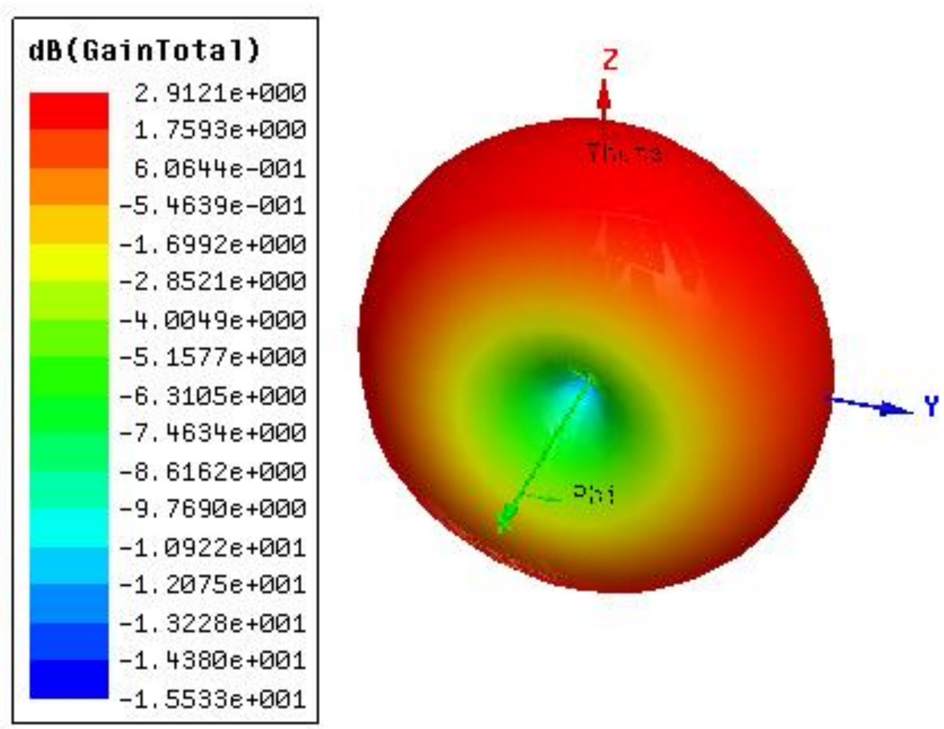


Fig 4.23 Satellite Dipole Antenna Gain.

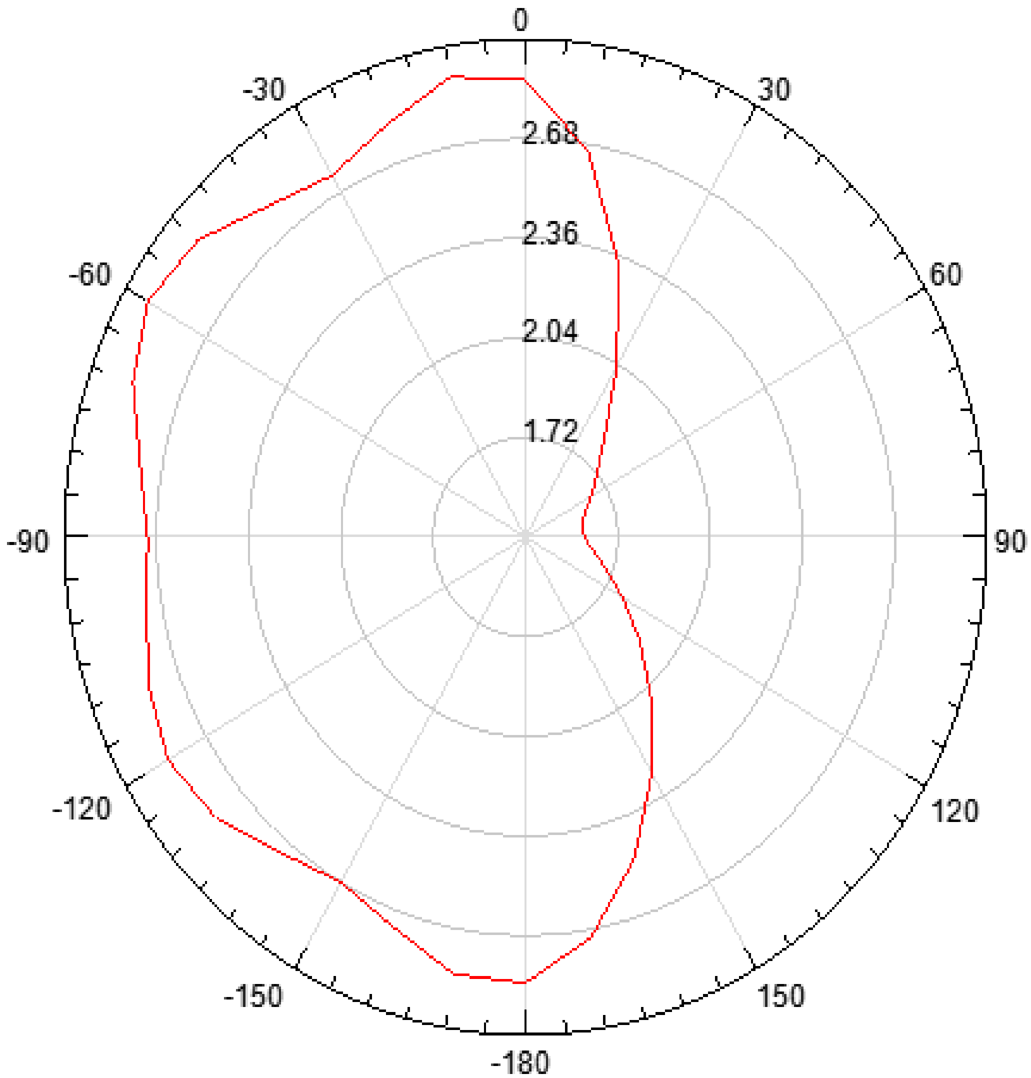


Fig 4.24 Radiation Pattern of Designed Dipole Antenna.

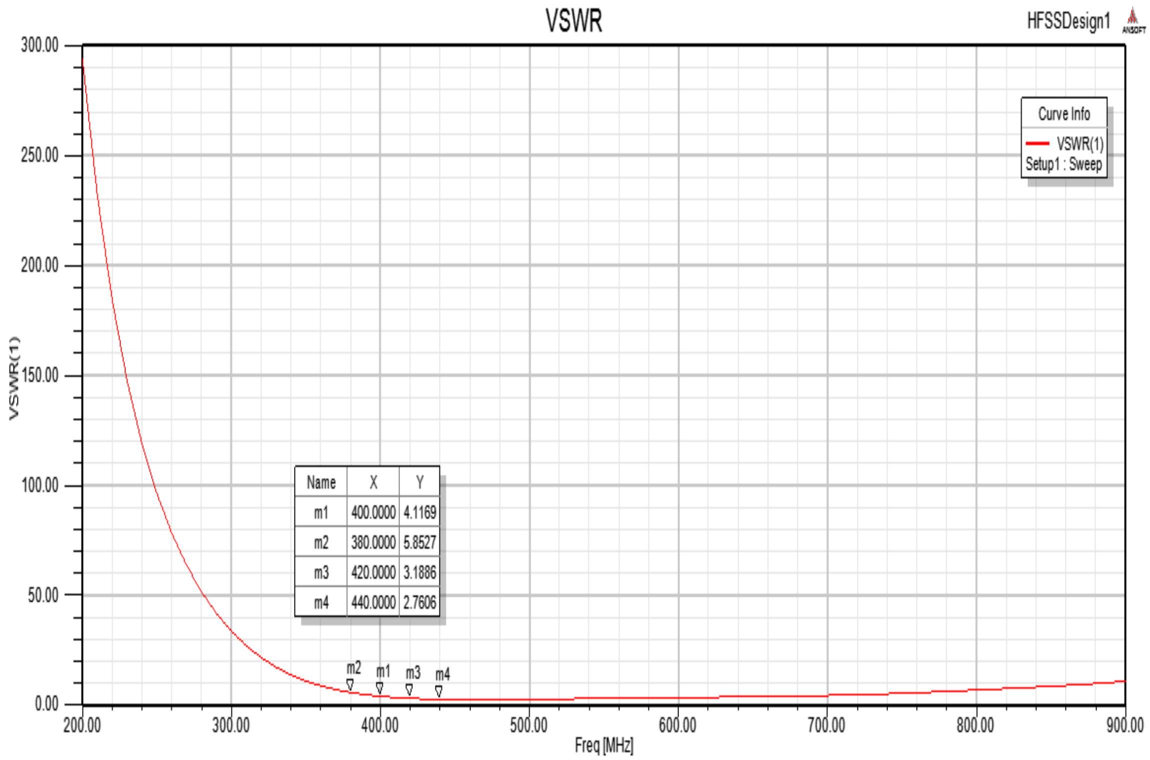


Fig 4.25 VSWR Values of Designed Antenna.

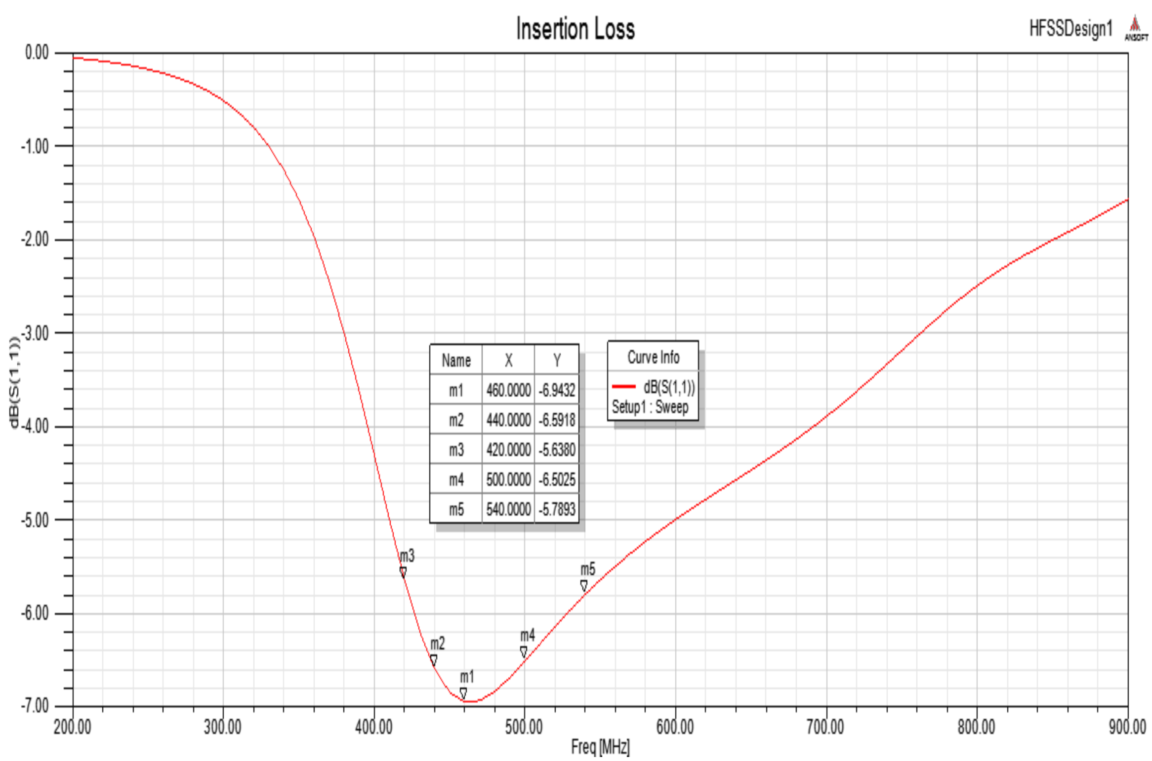


Fig 4.26 Designed Antenna Insertion Loss in dB.

Chapter Five: Conclusion and Future Work

5.1 Conclusions

TNC and AFSK have been designed based on Arduino to complete telemetry mission by transmit and receive data properly, this section verified by implementing Tx and Rx circuits with walkie talkie as an analog transmission. Also, UHF Mixer has been designed and obtained RF signal 433 MHz with -14.9dBm after adding matching networks at the input and output of mixer and applying BPF with 8dB gain at the output of mixer. Dipole antenna has been designed to meet ISRASAT1 specification with good results about 3dB gain, 2.9 VSWR and -5.9 dB as insertion loss, all of design procedures achieved after calculate the link budget design for 450km distance between CubeSat and ground with considered all losses and gains.

5.2 Future Work

For more optimization and enhancing the current work following tips may be very useful to go farther and achieve better results:

- 2-watt power amplifier design to further enhance link budget and system performance.
- Using patch antenna instead of wire dipole antenna.
- Optimization of matching network at the output port for the mixer.
- Design or selection of suitable ground station to track ISRASAT1 and receive its signal.

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[17] **project, MicroModem gethub-open source.***https://github.com/markqvist/MicroModem.* 7 December 2018.

Appendixes

Appendix A: Advanced Design System 2009 ADS

Advanced Design System is the world's leading electronic design automation software for RF, microwave, and high-speed digital applications. ADS pioneer the most innovative and powerful integrated circuit-3DEM-thermal simulation technologies used by leading companies in the wireless, high-speed networking, defense-aerospace, automotive and alternative energy industries. For 5G, IoT, multi-gigabit data link, radar, satellite and high-speed switched mode power supply designs, ADS provide an integrated simulation and verification environment to design high-performance hardware compliant with the latest wireless, high speed digital and military standards. For more detailed visit this website:

https://www.keysight.com/en/pc-1297113/advanced-design-system-ads?nid=-

Appendix B: High Frequency Structural System HFSS

HFSS 13.0 is an interactive software package for calculating the electromagnetic behavior of a structure. The software includes post-processing commands for analyzing this behavior in detail. Using HFSS, you can compute:

• Basic electromagnetic field quantities and, for open boundary problems, radiated near and far fields.

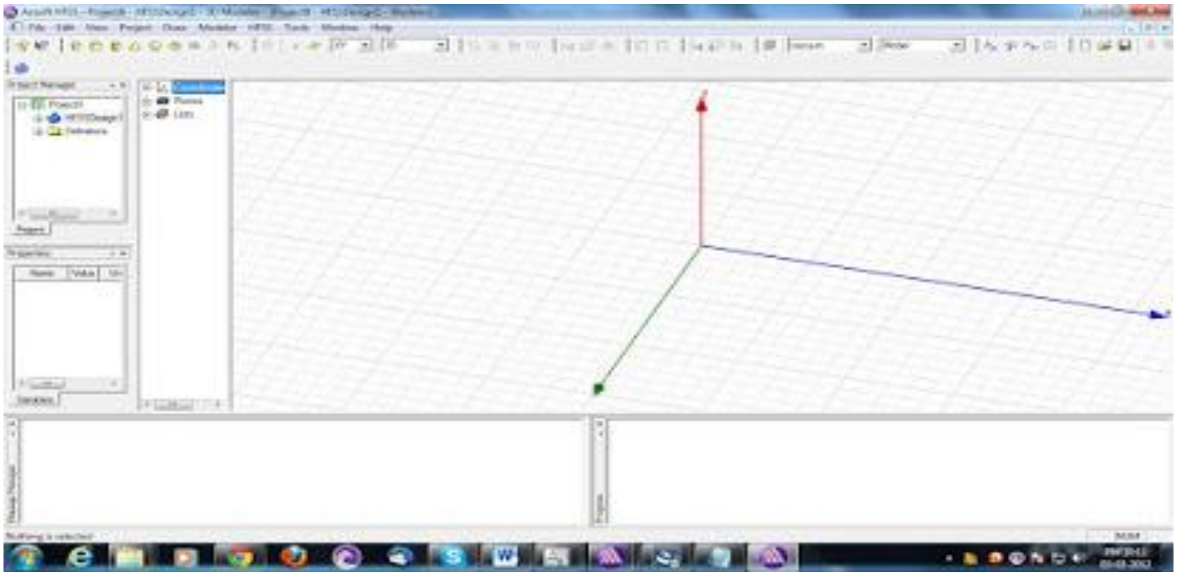
• Characteristic port impedances and propagation constants.

• Generalized S-parameters and S-parameters renormalized to specific port impedances.

• The eigenmodes, or resonances, of a structure.

You are expected to draw the structure, specify material characteristics for each object, and identify ports and special surface characteristics. HFSS then generates the necessary field solutions and associated port characteristics and S-parameters. For more information visit this web site:

https://www.ansys.com/products/electronics/ansys-hfss



Appendix C: BFR92A BJT Transistor

Silicon NPN Planar RF Transistor (Electrostatic sensitive device). D High power gain D Low noise figure D High transition frequency BFR92A Marking: +P2 Plastic case (SOT 1 = Collector, 2 = Base, 3 = Emitter BFR92AR Marking: +P5 Plastic case (SOT 1 = Collector, 2 = Base, 3 = Emitter
BFR92AW Marking: WP2 Plastic case (SOT 1 = Collector, 2 = Base, 3 = Emitter.

Tamb = 25_C, unless otherwise specified Parameter Collector-base voltage Collector-emitter voltage Emitter-base voltage Collector current Total power dissipation Junction temperature Storage temperature range Test Conditions Symbol VCBO VCEO VEBO IC Ptot Tj Tstg Value to +150 Unit mW °C.

Tamb = 25_C, unless otherwise specified Parameter Test Conditions Junction ambient on glass fibre printed board 1.5) mm3 plated with 35mm Cu Symbol RthJA Value 450 Unit K/W.

Tamb = 25_C, unless otherwise specified Parameter Collector cut-off current Collector-base cut-off current Emitter-base cut-off current Collector-emitter breakdown voltage DC forward current transfer ratio Test Conditions VCE 20 V, VBE = 0 VCB = 0 VEB = 1 mA, = 0 VCE 14 mA Symbol Min Typ Max Unit ICES 100 mA ICBO 100 nA IEBO 10 mA V(BR)CEO 15 V hFE 100 150

Tamb = 25_C, unless otherwise specified Parameter Transition frequency Collector-base capacitance Collector-emitter capacitance Emitter-base capacitance Noise figure Power gain Linear output voltage two tone intermodulation test Third order intercept point Test Conditions VCE = 14 mA, = 500 MHz VCB = 1 MHz VCE = 1 MHz VEB = 1 MHz VCE = 2 mA, = 800 MHz VCE ZL = ZLopt, = 14 mA, = 800 MHz VCE = 14 mA, dIM = 60 dB, = 806 MHz, = 810 MHz, 50 W VCE = 14 mA, = 800 MHz Symbol fT Ccb Cce Ceb F Gpe = V2 Min Typ Max Unit GHz dB mV.

For more details you can download BFR92A from:

https://www.digchip.com/datasheets/parts/datasheet/513/BFR92A-pdf.php